

INTERFERENCE & DIFFRACTION (Using a Laser)

Experiment may be booked as a one-weight or a two-weight experiment.

PART I. Interference in one dimension (1D) – 1 weight

REFERENCE: Randall D. Knight, *Physics for Scientists and Engineers: a Strategic Approach*, 2nd Edition, Chapters 21-22.



INTRODUCTION

The well-known phenomena of diffraction and interference have never previously been so easily demonstrated and measured as they are nowadays, using a laser light source. In particular, for so-called "Fraunhofer diffraction", a coherent source of parallel light is required and the laser provides such a source. Coherence, which is the extent (in space or time) to which the beam of light is in phase with itself, is necessary for the observation of interference.

Laser light is much more coherent than light from conventional sources. So coherent is laser light that one may observe interference effects even when the path difference between the interfering rays is much greater than 10^9 wavelengths!

THEORY

Light is electromagnetic wave and different rays of light can interfere with each other. If two waves are exactly "in phase" as shown in Figure 1a, they will reinforce each other; this is called *constructive interference*. In this case the difference in phase angle is 0° , or 360° (one full wavelength) or 720° (two wavelengths), or in radians it is $2\pi n$, where $n = 0, \pm 1, \pm 2 \dots$. The waves are shifted with respect to each other by an integer number of wavelengths.

If, however, they are exactly "out of phase", as shown in Figure 1b, they will cancel each other; this is *destructive interference*. In this case the difference in phase angle is 180° (half a wavelength), or 540° (one and a half wavelengths), or in radians it is $2\pi(n + \frac{1}{2})$, where $n = 0, \pm 1, \pm 2 \dots$. One wave is shifted relative to the other wave by the odd number of half wavelengths.

If their phase relationship is somewhere between these two extremes, some intermediate result will obtain.

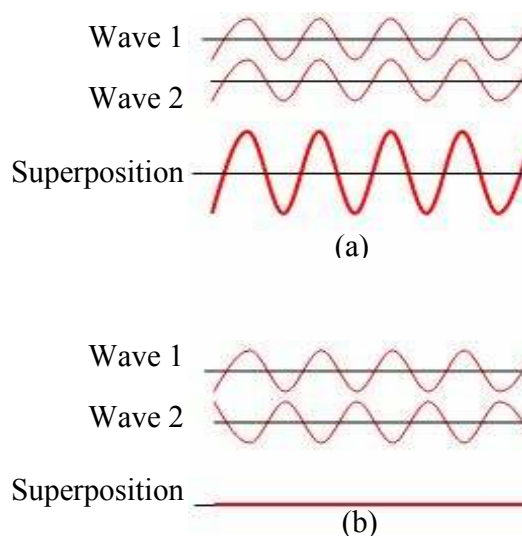


Fig.1. Interference of two coherent waves:
a – constructive interference;
b- destructive interference.

The simplest way to create condition for observation of interference is to place an obstacle with two slits in front of a source of light. The slits produce Wave 1 and Wave 2, which are coherent, because originate from same primary wave.

Due to the wave nature of light, the direction of travel of the incident wave changes after passing the slit or interacting with the edge of an obstacle. This phenomenon is called diffraction. Fraunhofer diffraction takes place when the incident wave has initially a plane wavefront, which is an imaginary surface perpendicular to the rays that form the beam of light. Behind the slit which width is bigger, but of the order of magnitude of the wavelength, initially parallel beam of light spreads in all directions as a cylindrical wave, emitted by a linear source, placed at the position of the slit (Fig.2). Diffraction does not change the wavelength of the incident wave.

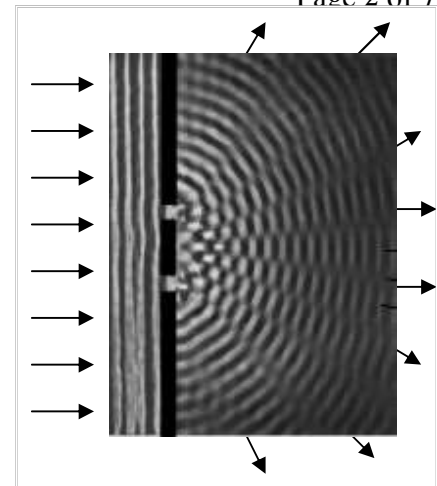


Fig. 2. Fraunhofer diffraction of a plane wave (left) on a double-slit system. Arrows show the direction of wave propagation.

a) ^s **Interference from a double-slit system.**

Figure 3a is a schematic diagram of Thomas Young's classical interference experiment. Light impinges on a screen which has two narrow slits **A** and **B** scribed on it, a distance **d** apart. At some distance **L** a screen is placed and the pattern of the light arriving at the screen can be observed. To observe interference due to Fraunhofer diffraction, **L** must be much greater than **d**. Consider what will be observed at a point on the screen, **P**, which is at a distance **x** from the centre of the screen. If **x** is zero (i.e. for the point at the exact centre of the screen) both rays **AP** and **BP**, travelled same distance, will arrive exactly in phase, and we will observe a maximum of light intensity. However, at a point **P** such as that shown in Figure 3a, the path of light ray **BP** is longer than the path of ray **AP**, and thus the two waves have different phase at **P**. If the path difference **BP-AP** = δ is an *even* number of half wavelengths, we will still observe a maximum of light intensity at **P**. If, however, δ is an *odd* number of half wavelengths, the waves will exactly cancel and there will be a minimum of intensity at **P**.

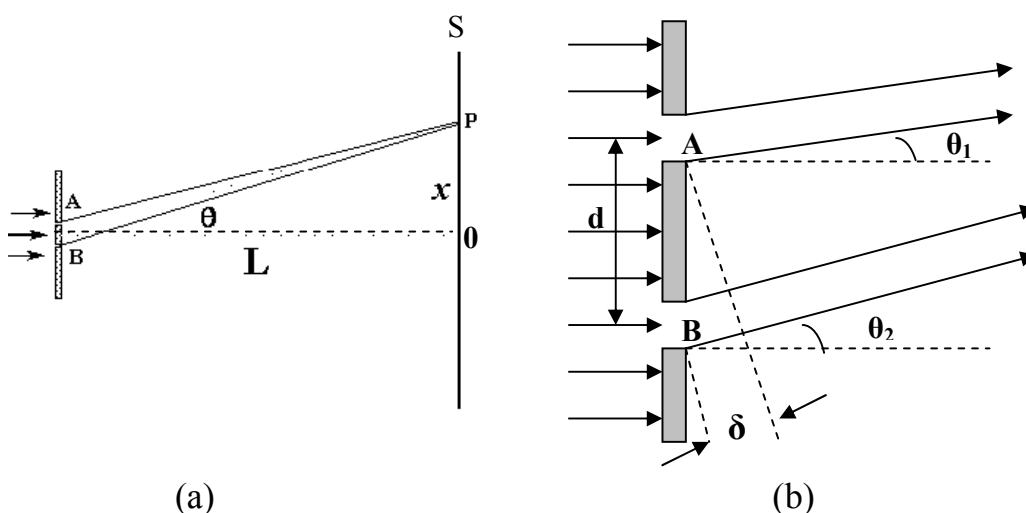


Fig. 3. Diffraction of the primary beam on the slits A and B produces interference pattern on the screen S behind the obstacle.

INTERFERENCE & DIFFRACTION

Now, consider Figure 3b, which is a blow-up of the region around two slits. For $L \gg d$, the approximation $\theta_1 \approx \theta_2 \approx \theta$ is accepted, and the rays from slit A and slit B can be considered parallel. Usually, the width of one slit is much smaller than d . Therefore, the rays from different points inside one slit are parallel as well. Also, at the small angles considered here, note that

$$\theta \approx \sin(\theta) \approx \tan(\theta).$$

The path difference δ is shown. The condition that we observe a minimum of intensity on the screen thus becomes: $\delta = (n + \frac{1}{2}) \lambda$ where $n = 0, 1, 2, 3, \dots$, and λ is the wavelength of the light.

Now, since $L \gg d$, $x/L = \tan(\theta) = \sin(\theta) = \delta/d$, the condition for a **minimum** in the interference pattern of light on the screen becomes:

$$xd/L = (n + \frac{1}{2}) \lambda \text{ with } n = 0, 1, 2, 3, \dots \quad (1)$$

Can you see what the corresponding relation for maxima is?

b) Diffraction from a single slit.

In the case of a single slit, light from different parts of the slit interfere with each other. To see how this might happen, consider dividing the slit into two zones as indicated in Fig. 4. Division into zones provides that a ray of light coming from the top of zone 1, XX' is exactly out of phase with a ray of light YY' coming from the same position in zone 2. Then the "next" ray of light from zone 1, xx' , will be out of phase with its corresponding ray in zone 2, yy' . Then we can imagine stepping through the zones from top to bottom till we have considered all the rays. In this particular case, each ray in zone 1 will have a corresponding ray in zone 2 which exactly cancels it out, leading to a minimum of intensity.

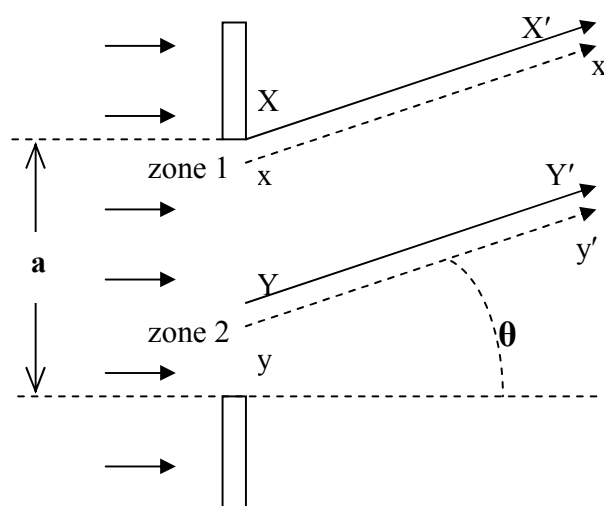


Fig.4. Single-slit diffraction of a plane wave.

By analogy with the case of the double slits, you should be able to derive the corresponding relation for a minimum of intensity on the screen at an angle θ . At the next largest angle at which there is a minimum, we can think of the slit being divided into four zones; then the rays from zones 1 and 2 cancel (they are $\lambda/2$ out of phase) as do the rays from zones 3 and 4. This argument can be continued, and you should be able to convince yourself that, if a is the width of the slit, **minima** in the diffraction pattern should be seen at positions x on the screen when:

$$xa/L = n \lambda \text{ with } n = 1, 2, 3, \dots \quad (2)$$

The relation for maxima is a bit more complicated, and the maxima do not lie exactly halfway between the minima, as is the case with the double slit system.

c) Interference pattern for diffraction on multiple-slit systems (Diffraction grating).

It is useful to analyze the interference pattern on the screen with the *Intensity vs. Position* graph as in Fig. 5. The single-slit diffraction pattern acts as an “envelope” for an N -slit interference pattern. For more than two slits the most intense maxima in the intensity are given by equations similar to those we have discussed above; small, subsidiary maxima begin to appear in the middle of the minima positions calculated by equation (1) above. The width of the maxima shrinks rapidly with an increase in the number of slits. When the number of slits intercepting the beam becomes large, the system is called a *diffraction grating*. A typical grating contains several thousand lines per centimeter. The intensity of the pattern on the screen is the result of the combined effects of interference and diffraction. Each slit produces diffraction, and the diffracted beams interfere with one another to form the final pattern. The condition for principle maxima is $d \sin \theta_{\text{bright}} = m\lambda$, where $m = 0, \pm 1, \pm 2, \dots$

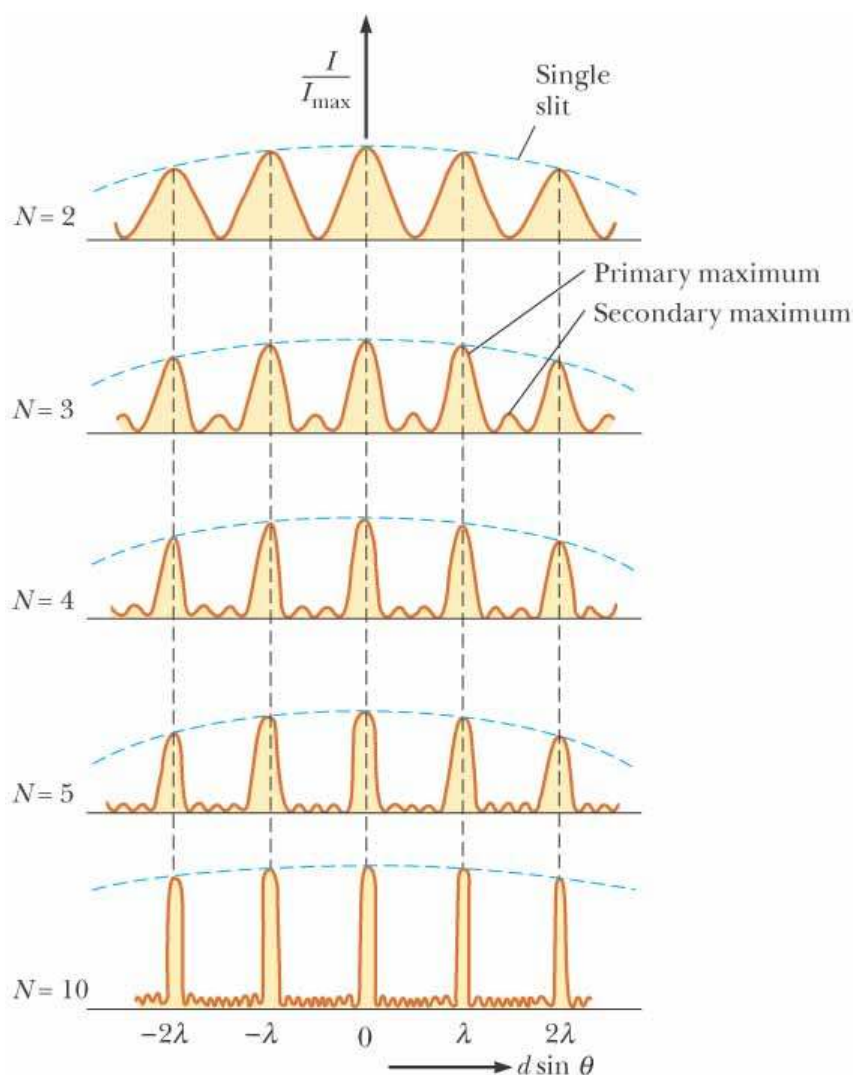


Fig.5. Interference pattern for Fraunhofer diffraction on a different number of slits.

(A good discussion of the patterns obtained, and a more careful calculation of the single slit pattern is given in the Reference, available at the **Resource Centre**).

All the above discussed interference patterns are 1-dimensional, because the intensity depends upon the distance along the direction of one axis perpendicular to the direction of slits (in our examples this direction was associated with x-axis).

Your task is to use the laser beam and a number of obstacles with different slits to observe the interference pattern and to determine the wavelength of the laser radiation by measuring x , L , d , a .

CAUTION: If viewed directly, the beam from even a low power laser will cause permanent damage to your vision. Never look directly into the beam.

Equipment: He-Ne laser; an aperture slit with variable width for a single-slit experiment; a set of slides with transparent slits and holes; a meter stick; a screen with graph paper; a microscope with digital scale (Fig. 6 and 7).

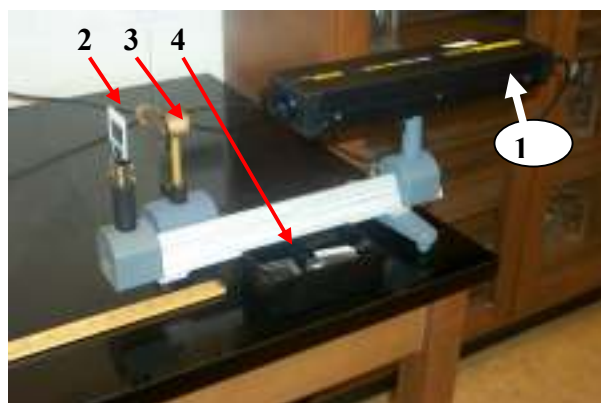


Fig. 6. 1 – laser;
2 – a holder for a frame with slits;
3 – a slit with a variable width;
4 – a kit of slides with different slits and patterns

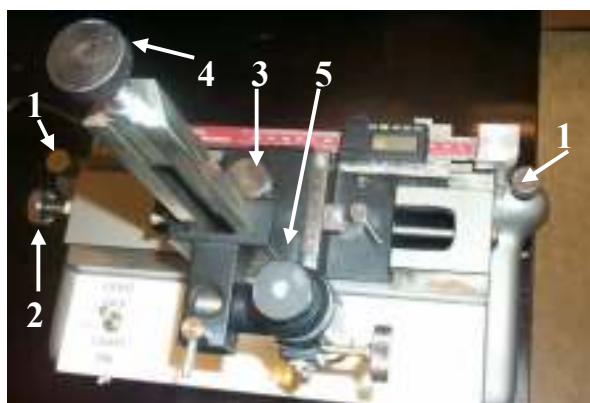


Fig. 7. Microscope:
1 – screws for leveling the table;
2 and 3 – screws for adjusting the position of the tube in horizontal plane;
4 – screw for coarse vertical positioning of the eyepiece;
5 – screw for focusing the eyepiece.

PROCEDURE

Exercises and measurements with the microscope do not need switching off the room lights.

Turn on the light on the microscope and adjust the position of the eyepiece above the illuminated spot. The screws 2 and 3 (Fig. 7) must be able to shift the tube with the eyepiece in horizontal plane. To exercise in reading the digital scale of the microscope, place the slide with Dot Apertures under the objective lens. Measure the diameter of the dot and compare it with the value, given on the slide.

Take a slide with a number of slits and measure the width of a slit and the separation between two slits for a set of double-slit patterns. Compare the width (w) of a slit and the slit separation (d) quantitatively. Do they match a condition $w \ll d$?

NOTE: One major contributor to the error is the precision with which you can measure the slit widths and spacing. Make sure that you understand how to focus the cross hairs, ensure that you have good illumination, and be clear about exactly the distances you want to measure. You should take several independent measurements of each quantity to give you a good mean value with its standard error.

Insert a slide with a set of double-slit patterns into a holder in front of the laser. Turn on the laser. It will take about a minute for the laser to warm up. For experiments with the laser, you may need to turn off the top lights in the room.

Changing the double-slit pattern within one slide in the way of the laser beam, observe qualitatively the interference patterns from the different slit systems. Adjust the position of the screen in such a way that it would permit you to measure the position of at least three central maxima on the screen with the graph paper. Use the meter stick and the measurements on the screen to determine the wavelength of the laser. You are expected to make measurements with at least three different double-slit patterns and calculate the mean value for the wavelength. Compare the obtained value to the one given on the side of the laser. Calculate the error of the measurements and the difference between the given wavelength and the calculated value.

Is your result precise?

Is your result accurate?

Replace the slide by the slit with variable width and adjust the position of the screen to obtain a clear position of the two central minima. Does equation (2) correctly predict what happens to the central maximum when the slit width is doubled or halved?

For a single slit diffraction measure the distance between two central minima on the screen and determine the wavelength of the laser light. Is your result accurate?

Babinet's Principle

Consider two “complementary” diffracting objects, a hole/slit and an obstacle of same size and shape. Babinet's Principle states that at any place on a detecting screen where the intensity is zero *in the absence of the two objects*, the diffraction pattern will be exactly the same when either of the complementary objects is used by itself. (In this experiment, in which the detecting screen is illuminated by a laser at some distance away, the intensity of the light, at points on the screen away from the centre of the beam is indeed close to zero. When the *Slit* or the *Obstacle* are interposed, however, the intensity at such points can be definitely non-zero, due to the diffraction maxima).

Using the value for the wavelength of light inscribed on the laser, in conjunction with equation (2) and Babinet's principle, determine the thickness of your hair. Compare that value with the value measured using the travelling microscope. How do these compare?

PART II. Diffraction grating and interference in two dimensions (2D) – 1 weight

REFERENCE: Randall D. Knight, *Physics for Scientists and Engineers: a Strategic Approach*, 2nd Edition, Chapters 21, Section 7; Chapter 22, Section 5; Chapter 25, Section 2.

INTRODUCTION

Theory of two- or three-dimensional diffraction is beyond the 1st year course of Physics. However, the references give a pretty simple and complete explanation of what you will observe and measure in the Part II of the experiment.

INTERFERENCE & DIFFRACTION

Equipment: He-Ne laser; a set of slides with different 2D-patterns, diffraction grating replica with 7500 lines per inch; a meter stick, a screen with graph paper; a microscope with digital scale.

Recommended objects to study are: diffraction grating; slide “Patterns”; slide “Random slits”; slide “Dot apertures”; slide “Regular square array of round holes”.

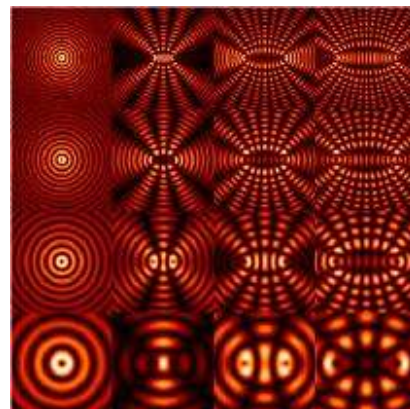
Mount the holder with the diffraction grating and make measurements with the meter stick and the graph paper on the screen to obtain the wavelength of the laser. Does the distance between the grating and the screen change the interference pattern on the screen? Why?

Calculate the wavelength of the laser using the data of the experiment with the diffraction grating. Compare the results, obtained with the double-slit system, the single-slit aperture and the diffraction grating. Which result is the most accurate?

The recommended slides with 2D-patterns can create a beautiful interference patterns on the screen. The patterns can be used to find the sizes of the holes or obstacles on the slide.

Try all the slides and obtain interference patterns on the screen. Make a sketch for each pattern and give the numerical data for the images on the screen, e.g. diameters of the rings, width of the maxima (distance between two adjacent minima).

How to obtain the diameters of the dots with the interference pattern? Compare the results of your measurements and calculations with the results given by the microscopic observation of the dots.



For a non-regular pattern on the slide, sketch the image on the screen. Interpret the 2D-interference pattern on the screen to make it possible to use it for calculating the numerical parameters of the holes or obstacles.

Name the main sources of error. How to decrease the error in calculations of the parameters of non-regular patterns?

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Completely updated by Natalia Krasnopolskaia in January 2010