Diffraction at a slit, at a post and at a circular iris diaphragm

Objects of the experiments

- Investigating diffraction at a slit at different slit widths and determining the slit width.
- Investigating diffraction at a post and confirming Babinet's principle.
- Investigating diffraction at a circular iris diaphragm at different hole diameters and determining the diameter of a hole.

Principles

The nature of light was a controversial issue for a long time. In 1690, Christiaan Huygens interpreted light as a wave phenomenon; in 1704, Isaac Newton described the light beam as a current of particles. This contradiction was resolved by quantum mechanics, and the idea of wave-particle duality came up. Diffraction experiments provide evidence of the wave character of light.

Diffraction phenomena always occur when the free propagation of light is changed by obstacles such as iris diaphragms or slits. The deviation from the rectilinear propagation of light observed in this case is called diffraction.

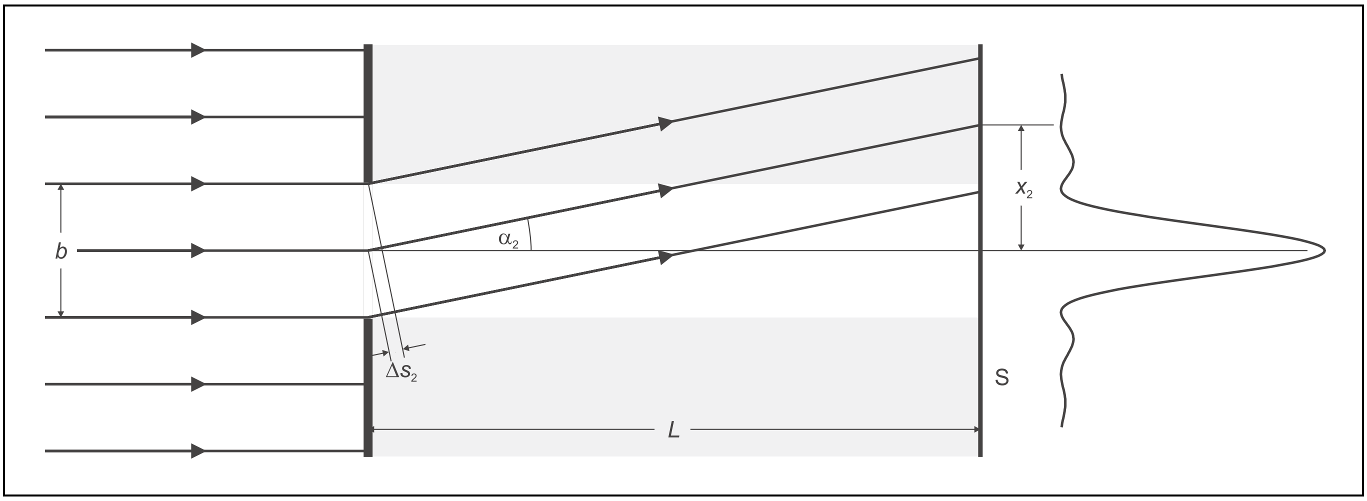
When diffraction phenomena are studied, two types of experimental procedure are distinguished:

In the case of *Fraunhofer* diffraction, parallel wave fronts of the light are studied in front of the diffraction object and behind it. This corresponds to a light source which is at infinite distance from the diffraction object on one side and, on the other side, the screen which, too, is at infinite distance from the diffraction object. Experimentally, this is realised with the aid of converging lenses, which are placed in the ray path, e.g., between the light source and the diffraction object.

In the case of *Fresnel* diffraction, the light source and the screen are at a finite distance from the diffraction object. With increasing distances, the Fresnel diffraction patterns are increasingly similar to the Fraunhofer patterns. Calculating the diffraction patterns in easier in the case of Fraunhofer diffraction. Therefore the experiments described here are based on Fraunhofer's point of view.

Diffraction phenomena can be clearly demonstrated by means of the intensive and coherent light of a laser. Diffraction of the incoming parallel light at the slit aperture causes the light to propagate also in the geometrical shadow (grey area in Fig. 1) of the slit diaphragm. Moreover, a pattern of bright and dark

Fig. 1 Schematic representation for the diffraction of light at a slit
b: slit width
L: distance between the screen and the slit
x_2: distance of the 2nd intensity minimum from the centre
α_2: direction in which the 2nd destructive interference is observed
Δs_2: path difference
S: screen



Apparatus

1 diaphragm with 3 single slits	469 91
1 diaphragm with 3 diffraction holes	496 96
1 diaphragm with 3 diffraction objects	469 97
1 He-Ne laser, linearly polarized	471 830
1 holder with spring clips	460 22
1 lens in frame, f = +5 mm	460 01
1 lens in frame, f = +50 mm	460 02
1 precision optical bench, 1 m	460 32
4 riders, H = 60 mm/B = 36 mm	460 353
1 translucent screen	441 53
1 saddle base	300 11

fringes is observed on the screen. This cannot be explained by the laws of geometrical optics.

An explanation is only possible if wave properties are attributed to the light and if the diffraction pattern observed on the screen is considered as a superposition of a (infinitely) great number of partial bundles coming from the slit aperture. In certain directions, the superposition of all partial bundles leads to destructive or constructive interference, respectively. Fig. 1 suggests a simple approach to make it plausible that dark fringes occur at positions where every partial bundle from one half of the slit is associated with exactly one partial bundle from the other half so that they cancel each other. For the partial bundles coming from the slit under the angle α_n, this is true in those cases where the path difference Δs_n between the central ray and the rim ray is an integer multiple *n* of half the wavelength λ of the light:

$$\Delta s_n = n \cdot \frac{\lambda}{2} \quad n = 1,2,3,\ldots \qquad \text{(I)}$$

For small diffraction angles α and a large screen distance *L*, we can use the approximation

$$\frac{2 \cdot \Delta s_n}{b} \approx \alpha_n \approx \frac{x_n}{L} \qquad \text{(II).}$$

Thus, from the condition for destructive interference (I), the wavelength is obtained:

$$\lambda = \frac{x_n}{n} \cdot \frac{b}{L} \qquad \text{(III).}$$

Safety notes

The He-Ne laser meets the requirements according to class 2 of EN 60825–1 “Safety of laser equipment”. If the corresponding notes of the instruction sheet are observed, experimenting with the He-Ne laser is safe.

- Never look into the direct or reflected laser beam.
- No observer must feel dazzled.

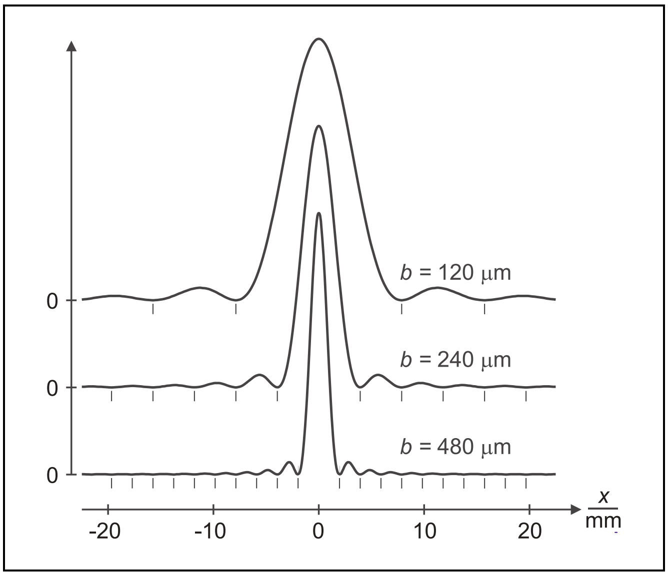
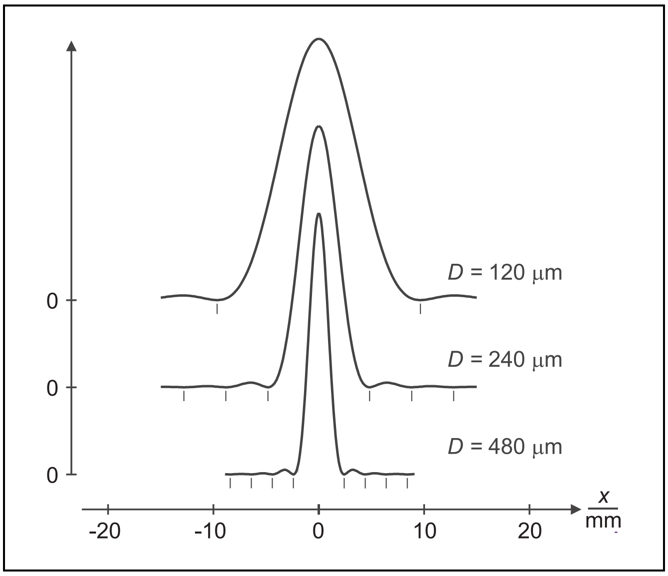


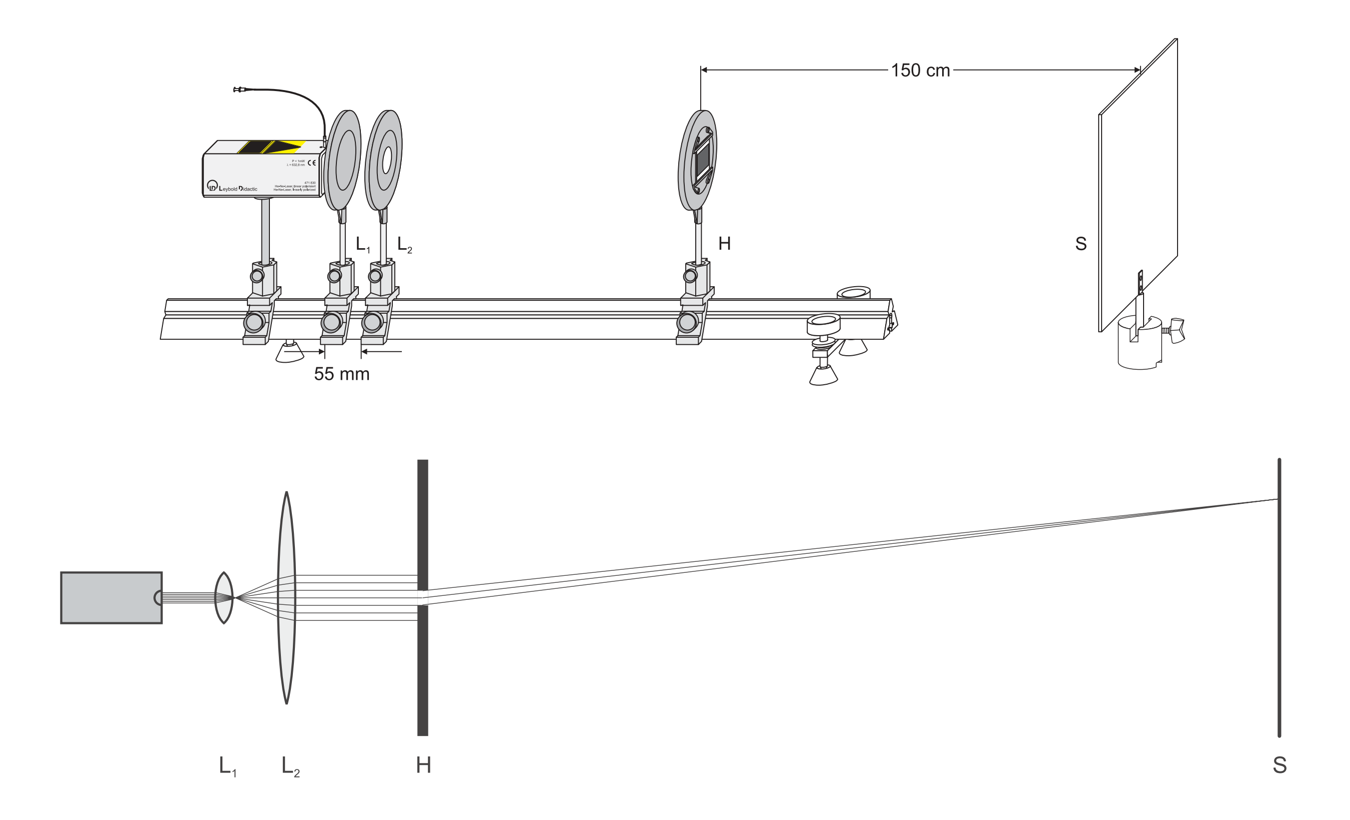
Fig. 2 Intensity of the diffraction pattern of the slit.

This relation establishes a connection between the wavelength λ and the geometry of the experiment. If the slit width *b* is known, Eq. (III) enables the wavelength λ to be determined. On the other hand, it is possible to determine the size of a diffraction object from a diffraction experiment with monochromatic light of known wavelength.

For an exact calculation of the diffraction pattern, the oscillation states of all partial bundles that come from the slit are added up, taking into account their phase differences. As a result the amplitude *A* of the field strength of the diffracted light is obtained at an arbitrary position *x* on the screen. From the amplitude distribution *A(x)* calculated this way, the intensity distribution $I(x) = A^2(x)$ is derived immediately. The intensity distribution on the screen is shown in Fig. 2 for different slit widths *b*. The intensity minima of the diffraction pattern are evenly spaced. The lower order intensity maxima are shifted towards the principal maximum of order zero. The higher the order, the closer lie the secondary maxima to the middle between two secondary minima.

Fig. 3 Intensity distribution of the diffraction pattern of a circular iris diaphragm (diametric section)





The diffraction at a post of equal width is complementary to the diffraction at a slit. Therefore the amplitude distribution $A'(x)$ of the diffraction pattern is complementary to the amplitude distribution $A(x)$ of a slit; i.e., the sum of $A(x)$ and $A'(x)$ is equal to the amplitude distribution $A_0(x)$ which would be observed on the screen without diffraction object (Babinet's principle). Outside the image of the light source on the screen, we have $A_0(x) = A(x) + A'(x) = 0$. Thus the associated intensities $I(x)$ and $I'(x)$ are equal in this area. In other words: in the area outside the image of the light source, the same diffraction pattern appears for the post and for the slit. That means, the relation (II) for diffraction at a slit holds in this case, too.

Diffraction phenomena at an iris diaphragm, too, can be clearly demonstrated with the aid of laser light. A special case, which plays a fundamental role for explaining diffraction at diffraction objects of arbitrary shape, is given by the ring pattern that arises when light is diffracted at holes with a circular boundary. However, even in this special case, the theoretical determination of the directions in which destructive or constructive interference occur is relatively involved in terms of mathematics. Therefore the result is quoted here without derivation. For destructive interference it reads:

$$\frac{d_n}{2 \cdot L} = k_n \cdot \frac{\lambda}{D} \qquad \text{(IV)}$$

with $k_1 = 1.220$, $k_2 = 2.232$, $k_3 = 3.238$, … and $n = 1,2,3,$ …

D = diameter of the iris diaphragm
d_n = diameter of the n-th dark ring
L = distance between the screen and the iris diaphragm

In fig. 3, a diametric section of the intensity distribution on the screen is shown for different hole diameters D. Here the intensity minima are not equally spaced as the coefficients k_n in Eq. (IV) do not exhibit equal distances. With increasing *n,* the distance approaches the value 1.

Fig. 4 Experimental setup (above) and schematic representation of the ray path (below) for observing diffraction at a slit, at a post and at a circular iris diaphragm.
L_1: lens f = +5 mm
L_2: lens f = +50 mm
H: holder for diffraction objects
S: screen

Setup

Remark: the adjustment should be carried out in a slightly darkened room.

The entire experimental setup is illustrated in Fig. 4. At first the spherical lens L_1 with the focal length f = +5 mm expands the laser beam. The subsequent converging lens L_2 with the focal length f = +50 mm is so positioned that its focus lies somewhat below the focus of the spherical lens. This leads to the laser beam being slightly expanded and running approximately parallel along the optical axis.

– Using a rider, mount the He-Ne laser to the optical bench as shown in Fig. 4.
– Set up the screen S at a distance of approx. 1.90 m from the laser.
– Direct the laser towards the screen, and switch it on.
– Place the holder for diffraction objects H on the optical bench at a distance of approx. 50 cm from the laser with the diaphragm with 3 single slits being clamped.
– Adjust the height of the laser so that the laser beam passes the middle of the diaphragm.
– Place the spherical lens L_1 with the focal length f = +5 mm in front of the laser at a distance of approx. 1 cm (the laser light has to cover the diaphragm).

- Remove the holder H for diffraction objects.
- Position the converging lens L_2 with the focal length f = +50 mm behind the spherical lens L_1 at a distance of approx. 55 mm, and displace it along the optical bench towards the spherical lens L_1 until the laser beam is imaged sharply on the screen.
- Displace the converging lens L_2 on the optical bench somewhat further towards the spherical lens L_1 until the diameter of the laser beam on the screen is approx. 6 mm (now the laser beam should have a constant circular profile along the optical axis).
- In order to check whether the beam diameter of the laser is constant between the lens and the screen, hold a sheet of paper in the ray path and follow the profile of the laser beam along the optical axis.

- Put the holder for diffraction objects back into the ray path and displace it until the distance between the screen and the diffraction object is 1.50 m.
- If necessary, displace the lens L_2 slightly until the diffraction pattern is imaged sharply.

Carrying out the experiment

a) Diffraction at a slit:

- On after another insert the slits C (b = 0.48 mm), B (b = 0.24 mm) and A (b = 0.12 mm) in the ray path, and observe the diffraction phenomenon in dependence on the slit width b.

- Insert the slit B again, and image the diffraction pattern sharply on the screen.
- Hold a sheet of paper on the screen, and, using a soft pencil, mark the locations of the intensity minima (dark fringes).
- Measure the distances x_n and calculate the values x_n/n.

b) Diffraction at a post:

- One after another insert the posts B (b = 0.4 mm) and A (b = 0.2 mm) in the ray path.
- Observe the diffraction phenomenon, and compare it with that of the slit.

c) Diffraction at a circular iris diaphragm:

- One after another insert the iris diaphragms C (D = 0.48 mm), B (D = 0.24 mm) and A (D = 0.12 mm) in the ray path, and observe the diffraction phenomenon in dependence on the hole diameter D.

- Insert the iris diaphragm C again, and image the diffraction pattern sharply on the screen.
- Hold a sheet of paper on the screen, and, using a soft pencil, mark the locations of the intensity minima (dark rings).
- Measure the diameters d_n of the dark rings and calculate the values d_n/k_n.

Remark: Sometimes the ring pattern appears to be somewhat distorted since slight deviations of the hole from the circular shape make themselves felt.

Measuring example

a) Diffraction at a slit:

With decreasing slit width b, the intensity in the centre becomes weaker. The intensity maxima become broader, and the distance between the intensity minima increases. That means the diffraction pattern moves more and more into the geometric shadow of the slit diaphragm.

Table 1: Distances x_n of the intensity minima from the intensity maximum of order zero

Order of the intensity minimum	$\frac{x_n}{\text{mm}}$	$\frac{x_n/n}{\text{mm}}$
1	4.5	4.50
2	8.5	4.25
3	12.5	4.17
4	16.1	4.03
5	20.0	4.00
6	23.5	3.92
7	27.5	3.93
8	31.5	3.94

Mean value: $\left\langle \frac{x_n}{n} \right\rangle$ = 4.093 mm

Wavelength: λ = 633 nm

Distance of the screen: L = 1.50 m

b) Diffraction at a post:

Apart from the principal maxima in the centre of the diffraction pattern, the diffraction patterns of the post correspond to those of the single slit.

c) Diffraction at a circular iris diaphragm:

With decreasing hole diameter D, the intensity in the centre becomes weaker. The bright rings become broader, and the distance between the dark ones increases. The diffraction pattern moves more and more into the shadow of the iris diaphragm.

Table 2: Diameters d_n of the intensity minima

Order of the intensity minimum	$\frac{d_n}{\text{mm}}$	$\frac{d_n / k_n}{\text{mm}}$
1	4.8	3.93
2	8.6	3.85
3	12,5	3,86

Mean value: $\left\langle \frac{d_n}{k_n} \right\rangle$ = 3.883 mm

Wavelength: λ = 633 nm

Distance of the screen: L = 1.50 m

Evaluation

a) Diffraction at a slit:

With the measured values

$\left\langle \frac{x_n}{n} \right\rangle = 4.093$ mm
$\lambda = 633$ nm
$L = 1.50$ m

the slit width b is obtained after rewriting Eq. (III):

$$b = \frac{\lambda \cdot L}{\left\langle \frac{x_n}{n} \right\rangle} = 0.23 \text{ mm}$$

b)

see measuring example

c) Diffraction at a circular iris diaphragm:

With the measured values

$\left\langle \frac{d_n}{k_n} \right\rangle = 3.883$ mm
$\lambda = 633$ nm
$L = 1.50$ m

the hole diameter D is obtained after rewriting Eq. (IV):

$$D = \frac{\lambda \cdot L}{\left\langle \frac{d_n}{k_n} \right\rangle} = 0.49 \text{ mm}$$

Results

a) Diffraction at a slit:

When laser light passes a slit, a diffraction pattern of fringes appears on the screen.

Outside the centre, too, bright fringes are observed. The distance of these fringes from the centre is the greater, the smaller the slit width is.

Thus, in the case of small slit widths, intensity is also observed on the screen at positions that would lie in the shadow of the slit diaphragm according to the laws of geometrical optics.

b) Diffraction at a post:

Diffraction at a post is complementary to the diffraction at a slit. Therefore the diffraction patterns are equal outside the image of the light source on the screen.

c) Diffraction at a circular iris diaphragm:

When laser light passes a circular iris diaphragm, a diffraction pattern of concentric rings appears on the screen.

Outside the centre, too, bright rings are observed. The distance of theses rings from the centre is the greater, the smaller the diameter of the hole is.

Thus, in the case of smaller hole diameters, intensity is also observed at positions that would lie in the shadow of the iris diaphragm according to the laws of geometrical optics.

Supplementary information

a) The wave model of light gives a descriptive explanation of all phenomena associated with the propagation of light, including the simple phenomena known from geometrical optics. The applicability is not limited to the region of the visible spectrum, but comprises the entire field of the electromagnetic spectrum from radio waves to ionizing radiation.

b) From Eq. (III) it is seen that the diffraction phenomena are particularly distinct if the wavelength of the light is of the order of magnitude of the diffraction object and the greater the wavelength of the light used is.

c) Between the coefficients k_n in Eq. (IV) and the zeros of the first order Bessel function $J_1(z)$ the following relation holds: $z_n = k_n \cdot \pi$.