EXPERIMENTING FROM A DISTANCE IN CASE OF DIFFRACTION AND INTERFERENCEù

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Abstract. Diffraction and interference are basic phenomena of waves. They are treated in wave optics extensively, because experimental setups are easy to built, diffraction patterns are visible and because of their importance for further subjects at school and university (diffraction of x-rays, cristallography, Fourier-Transformation, …). Unfortunately, in many cases the experiments are demonstration experiments with a few diffracting objects and not enough possibilities for the students to participate. Therefore we developed a very flexible Remotely Controlled Laboratory (RCL) about diffraction and interference - a real experiment, which can be performed over the internet. The user can choose from among 5 different wavelengths, about 150 diffracting objects and 3 different techniques of qualitative and quantitative measurement. In this contribution we describe the experimental setup, give an overview about experimental results and end with the added value of the experiment.

1. Introduction

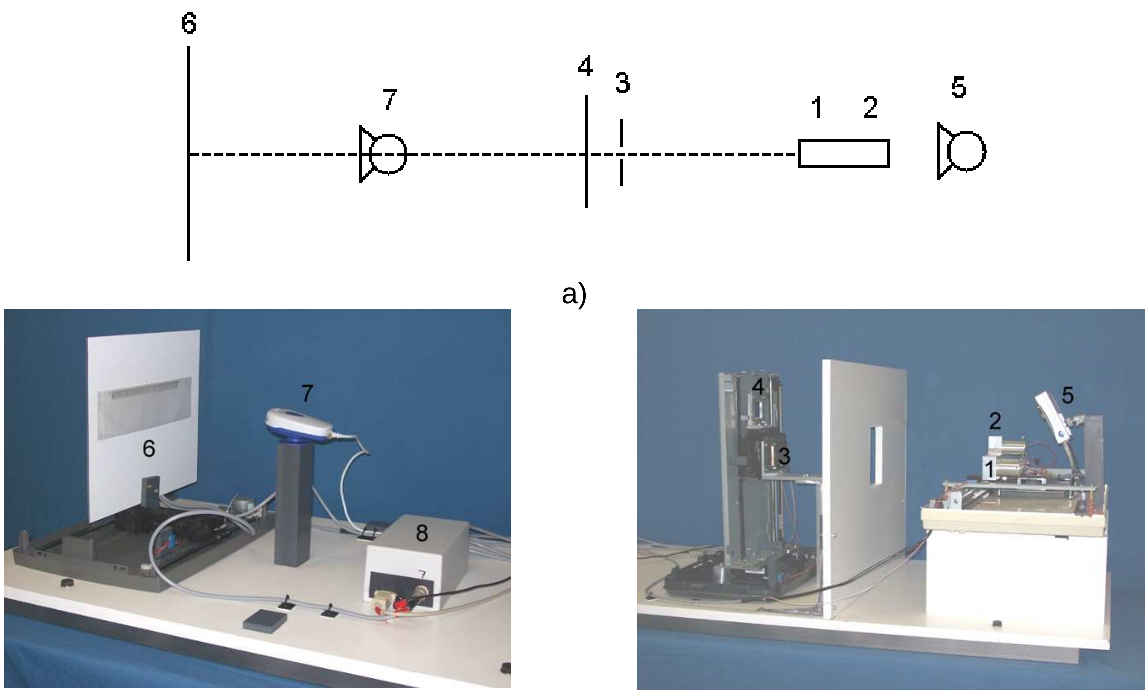
Diffraction and interference are phenomena, which play a significant role not only in pure physics (wave optics, optical spectroscopy), but also in technical applications e.g. coating of eyeglasses or resolution of microscopes. In addition we know of many interference phenomena in nature such as the colour of butterfly wings or aureoles around the sun or the moon. Diffraction as well as interference can be nicely modelled in wave optics (intensity distribution on a screen due to diffraction of light by objects, optical path difference, etc.). Consequently all theoretical results (intensity function of single slit and grating, calculation via Fourier-Transformation) can be checked by the results of quantitative measurements, in principle. Therefore this subject is intensively taught at school and university level in lectures as well as in student labs.

The experimental setup is comparatively simple and is mostly used in teaching in a qualitative manner: e.g. transition of the intensity distribution caused by a single slit, double slit, multiple slits and gratings, which students are watching on a wall in a class. Unfortunately these experimental setups do not incorporate all necessary technical parameters from theory such as different wavelengths for a deeper comparison of theoretical and experimental results. In general there is not available a complete set of diffracting objects of industrial grade to systematically investigate theoretical dependence on slit width, slit distance and number of slits. The laser granulation in the central maximum and the relative poor quality of photographically produced objects (like contrast ratio) do not always allow quantitative measurements (e.g. subsidary maxima for $n \geq 3$, intensity ratio between main maxima).

2. RCL variant

Therefore we developed, set up and tested a technically very comprehensive experiment for diffraction and interference in an RCL variant. An RCL experiment (Remotely Controlled Laboratory) is a real experiment at location A which can be controlled by a user from his computer via the internet at location B. The interested reader may have a look at our two basic papers describing the technical solution, the programming, concept, aims and experiences as well as didactical approach [1, 2]. Our portal [3] now offers about 20 RCL experiments such as "Speed of Light" or "Photoelectrical Effect".

Figure 1 shows the experimental setup, which is a standard setup with light source, diffracting object and screen in Fraunhofer diffraction manner. As light sources we offer 5 different laser diodes with wavelengths λ = 532 nm, 635 nm, 670 nm, 780 nm, 850 nm and power $P \approx$ 3 mW. On top of the laser diode λ = 670 nm we placed a second laser diode λ = 635 nm for studying the resolution of a grating.



b)

Figure 1. a) Sketch from top view of experimental setup. b) Pictures and components of left and right part of experimental setup: 5 laser diodes 532 nm – 870 nm (1), laser diode 635 nm (2), quadratic diaphragm (3), object holder with diffracting objects (4), webcam-1 (5), screen with light sensor and illuminated ruler (6), webcam-2 (7) and interface (8).

Table 1. Geometry of standard, resolving power (r) and special (s) diffracting objects.

Slit number N	Slit width b in µm	Slit distance d in µm
1	1, 5, 10, 15, 20, 25, 30, 60, 90, 800	-
2	1	60
	10, 15	20, 30, 40, 60, 90
	20, 25	30, 40, 60, 90
	30	40, 60, 90
3, 4, 5, 6	10, 15	20, 30, 40, 60, 90
	20, 25	30, 40, 60, 90
	30	40, 60, 90
10	5	10, 20, 30, 40, 50, 60, 80
	10	20, 30, 40, 50, 60, 80
	20	30, 40, 50, 60, 80
4, 5, 6, 8, 10, 12 (r)	5	60
1 wire (s)	90	-
2 (s)	15 and 20	60
	5 unknown objects (s)	

157 diffracting objects are arranged on a plate of glass (size 5 cm x 5 cm), which can be moved horizontally and vertically via stepper motors to select an individual diffracting object. Instead of diffracting objects produced by photo lithography [4] our diffracting objects were produced by electron lithography from an institute at the Technical University of Kaiserslautern [5]. The

advantages are much better resolving power and better contrast. The use of a lens is not necessary, because of the small size of the diffracting objects. Table 1 shows the geometry (slit number N, slit width b, slit distance d) of the diffracting objects, which we selected such that investigations cover all theoretical predictions. They are divided into 3 groups: 134 standard objects, 6 different pairs of objects to study the resolving power of a grating and 7 special objects like a wire, an asymmetric double slit and 5 unknown objects to determine their geometry. The diffraction pattern on screen and its intensity distribution can be investigated with three techniques of measurement:

- qualitative observation by eye via webcam-1 and taking a screenshot for further analysis
- observation by eye via webcam-1 and use of an illuminated ruler for direct quantitative reading and measuring
- quantitative measurement of intensity by a light sensor behind a little hole in the screen.

To study the resolving power of a grating two laser beams from laser diodes with wavelengths 635 nm and 670 nm irradiate the same diffracting object and the diffraction patterns are superimposed on one another on the screen.

3. Experimenting and results

Figure 2 shows the laboratory website of this RCL. With the control panel on the right the user can perform the experiment. First, selection of desired wavelength: In the picture of the lower webcam-2 one can observe the horizontal adjustment of the laser diode and how the laser spot irradiates the quadratic diaphragm in front of the diffracting objects. Second, choice of diffracting object among the three groups (table 1): In the lower webcam-2 picture one can watch the object holder moving in vertical and horizontal directions to find the chosen diffracting object. Simultaneously the diffraction patterns of all the diffracting objects illuminated during the movement appear in the upper webcam-1 picture. Third, choice of technique of measurement: One can switch on or off the illuminated ruler, take a screenshot of the diffraction pattern or choose a step size for a measurement with the light sensor. In the last case a white LED marks the horizontal position of the light sensor during its motion over the diffraction pattern. The intensity distribution is automatically displayed in a diagram and one can download the measured data as a text file. In the RCL we can only work with small diffraction angles $\alpha < |\alpha_{max}| = 4.5°$ because the distance e between screen and diffracting objects is 1.005 m and the horizontal width of the diffraction pattern, which can be viewed via webcam-1, is about 16 cm.

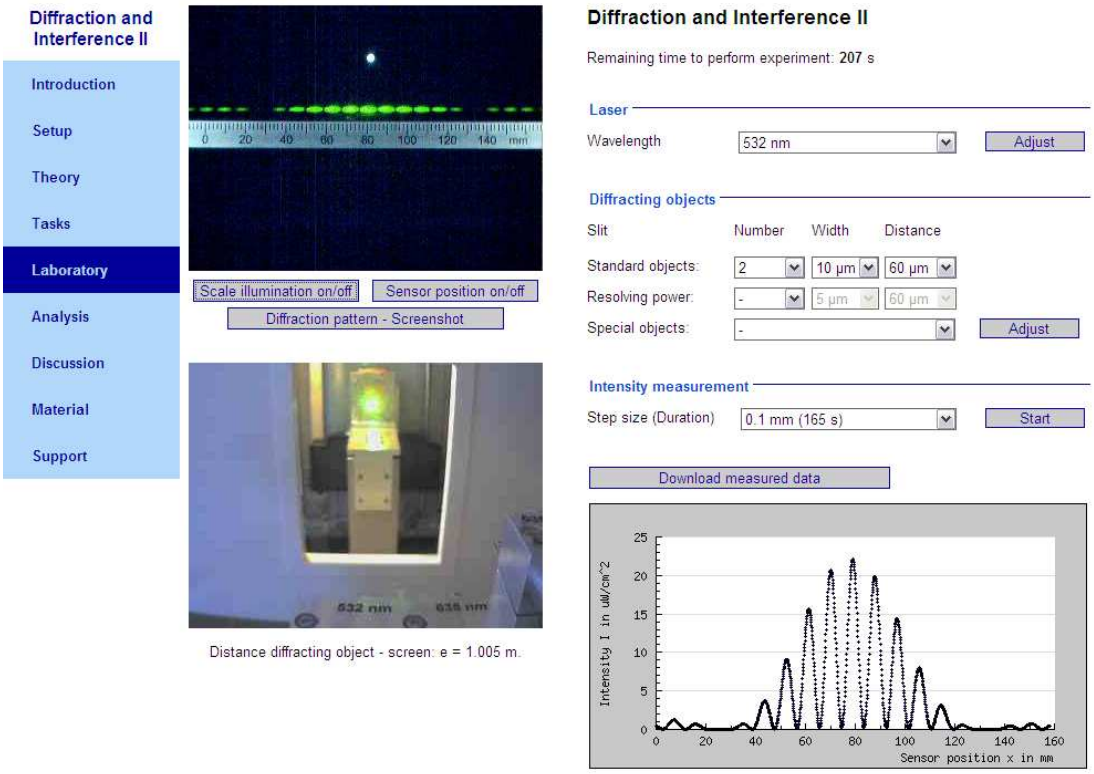


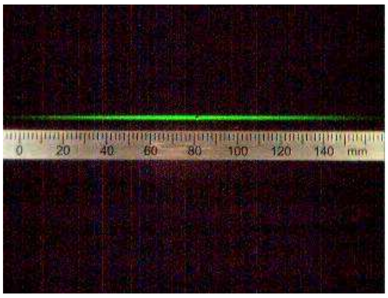
Figure 2. From the RCL website, menu item "Laboratory": RCL menu (left), view of webcams (middle) and control panel to vary technical parameters (right).

On the far left one can see the RCL menu (Introduction, Setup, Theory, Tasks, Laboratory, Analysis, Discussion, Material, Support), which is identical in all RCLs and contains all necessary information to perform the experiment autonomously. The following subsections demonstrate how

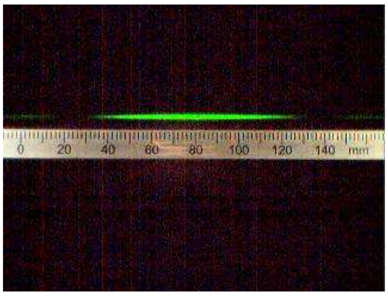
- one can check all kinds of theoretical predictions for a slit or grating
- one can use the different techniques of measurement
- accurate measured data for further analysis are
- flexible and comprehensive one can set up a measuring program
- quickly one can collect sufficient data for measuring series.

3.1 Investigations with single slit

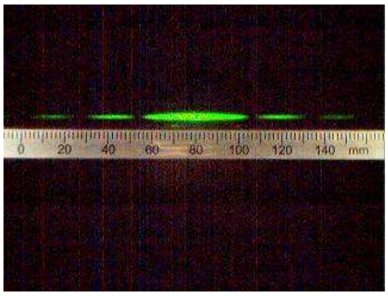
In figure 3 we deal with the diffraction pattern of a single slit. Qualitatively with increasing slit width b all maxima and minima of order n are moving closer to the central maximum (n = 0). Moreover the intensity of the maxima of order n is increasing. One can assume for the limiting case $b \rightarrow 0$ ($b << \lambda$) that the intensity distribution becomes a constant and zero. For the limiting case $b >> \lambda$ ($b \rightarrow \infty$ makes no sense) we get the intensity distribution of a geometrical shadow.



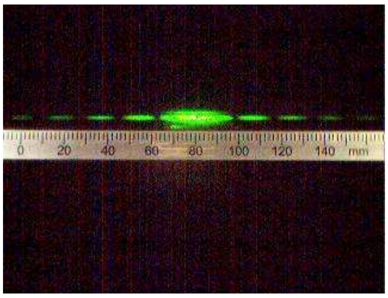
b = 5 µm



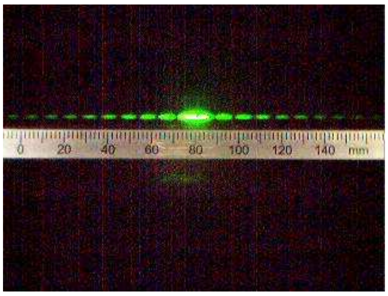
b = 10 µm



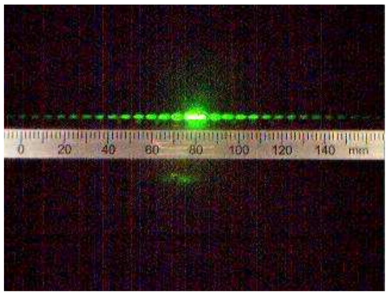
b = 20 µm



b = 30 µm

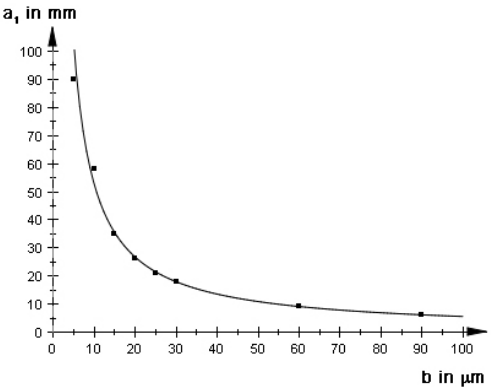


b = 60 µm

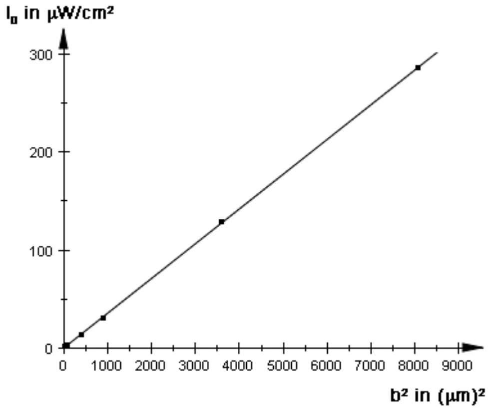


b = 90 µm

Figure 3. N = 1, λ = 532 nm. Diffraction patterns for increasing slit width b.



a)



b)

Figure 4. a) N = 1, λ = 532 nm. Distance a_1 between minimum of order n = 1 and central maximum versus slit width b. Comparison between measured (squares) and theoretical data (line).
b) N = 1, λ = 532 nm. Intensity I_0 of central maximum versus slit width b. Proof of $I_0 \sim b^2$ for measured data (squares) and regression line.

To investigate the first observation quantitatively we measured with the ruler the distance a_1 between the minimum of order n = 1 and the central maximum of order n = 0 (figure 4a). The experimental data fit very well to the theoretically derived dependence

$$\sin\alpha_1 = \frac{\lambda}{b} \approx \tan\alpha_1 = \frac{a_1}{e} \Leftrightarrow a_1(b) = \frac{e\lambda}{b}. \qquad (1)$$

To investigate the second observation quantitatively we measured with the light sensor the intensity I_0 of the central maximum for different slit width b (figure 4b). The measured data and the regression line show that $I_0 \sim b^2$, which confirms the theoretical prediction for a rectangular diaphragm with area $A = cb$ and constant height c that $I_0 \sim A^2 = (cb)^2 \sim b^2$ [6].

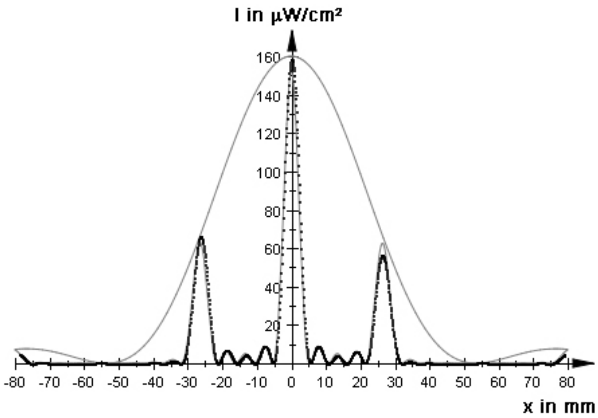
3.2 Structure of intensity distribution of a grating

The final step in our considerations here will be the quantitatively measured intensity distribution of a grating. In figure 5a we compare a typical intensity distribution with the well known theoretical prediction described by

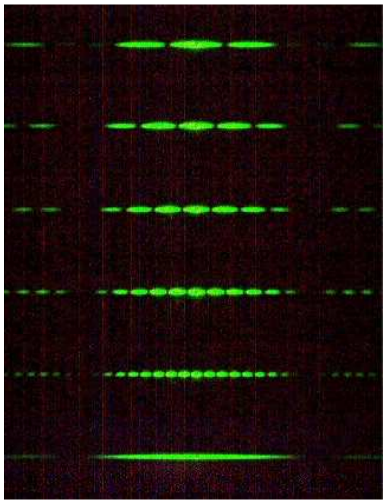
$$I(\alpha)=I_0\cdot\left(\frac{\sin(\frac{\pi b}{\lambda}\sin\alpha)}{\frac{\pi b}{\lambda}\sin\alpha}\right)^2\cdot\left(\frac{\sin(N\frac{\pi d}{\lambda}\sin\alpha)}{\sin(\frac{\pi d}{\lambda}\sin\alpha)}\right)^2 \quad (2)$$

and $\tan\alpha = x/e$. Measured data and theoretical line fit very well.

To qualitatively develop step by step the intensity distribution of a grating we start with a double slit (N = 2), because subsidiary maxima are missing. We took a sequence of screenshots of a double slit for constant slit distance *d* and different slit width *b* (figure 5b, upper pictures) and compare those to screenshots of a single slit with the same slit width *b* (figure 5b, lower picture). We can recognize that the diffraction pattern of the single slit is modulating the ideal intensity distribution of the double slit. In figure 5c we keep the slit width *b* constant and vary the slit distance *d*. Now the fine structure in the intensity distribution is determined by the property of the double slit. If d is small the spacing between maxima is high and if d is large the spacing is small.



a)



d = 20 um

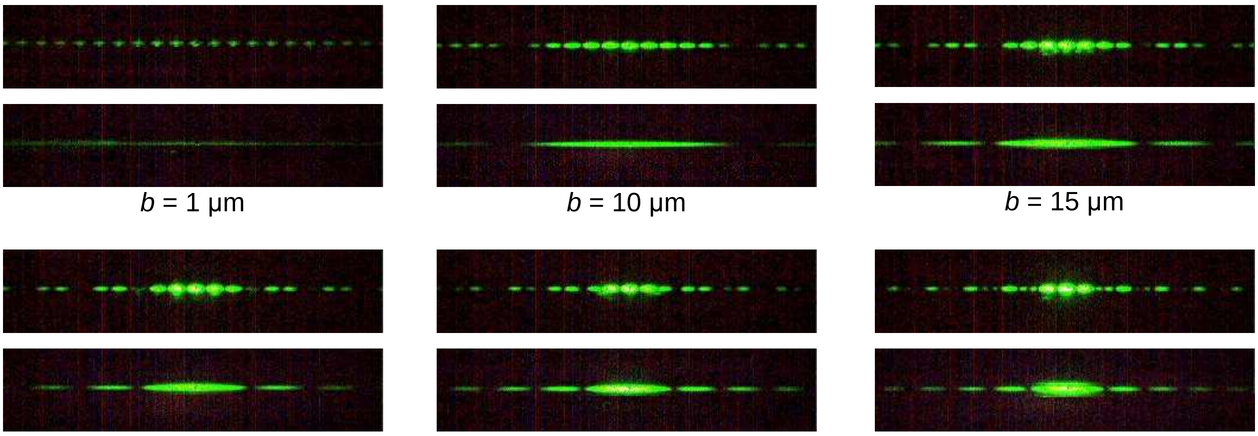
d = 30 um

d = 40 um

d = 60 um

d = 90 um

c)



b = 1 µm | *b* = 10 µm | *b* = 15 µm

b = 20 µm | *b* = 25 µm | *b* = 30 µm

b)

Figure 5. a) λ = 532 nm, N = 5, b = 10 µm, d = 20 µm. Comparison of measured (black points) and theoretical intensity distribution of grating with slit function (grey lines). I(0) of theoretical intensity distribution adapted to measured intensity distribution.

b) λ = 532 nm. Comparison between diffraction pattern of double slits with constant slit distance d = 60 µm and single slits of same slit width b for increasing b.
c) λ = 532 nm. Comparison of diffraction pattern of double slits with constant slit width b = 10 µm for increasing slit distance d (single slit with the same slit width).

3.3 Transition between real and ideal grating

Half-quantitatively, we study in figure 6 the transition between a real and an ideal grating ($N \rightarrow \infty$ and $b \rightarrow 0$). As a first step we increase in figure 6a the slit number *N* for constant slit width *b*: one can see, that the number of subsidary maxima is increasing and their relative intensity is decreasing. As a second step we decrease in figure 6b the slit width *b*: due to the expanding intensity distribution of the single slit envelope the relative intensity of main maxima n $\neq$ 0 is increasing and the first missing main maximum is shifted to greater distance |x|. For the limiting case of an ideal grating we get a diffraction pattern, which consists of equidistant “points” with intensity zero, whereas the mathematical representation of the intensity pattern is a function with equidistant delta-type maxima.

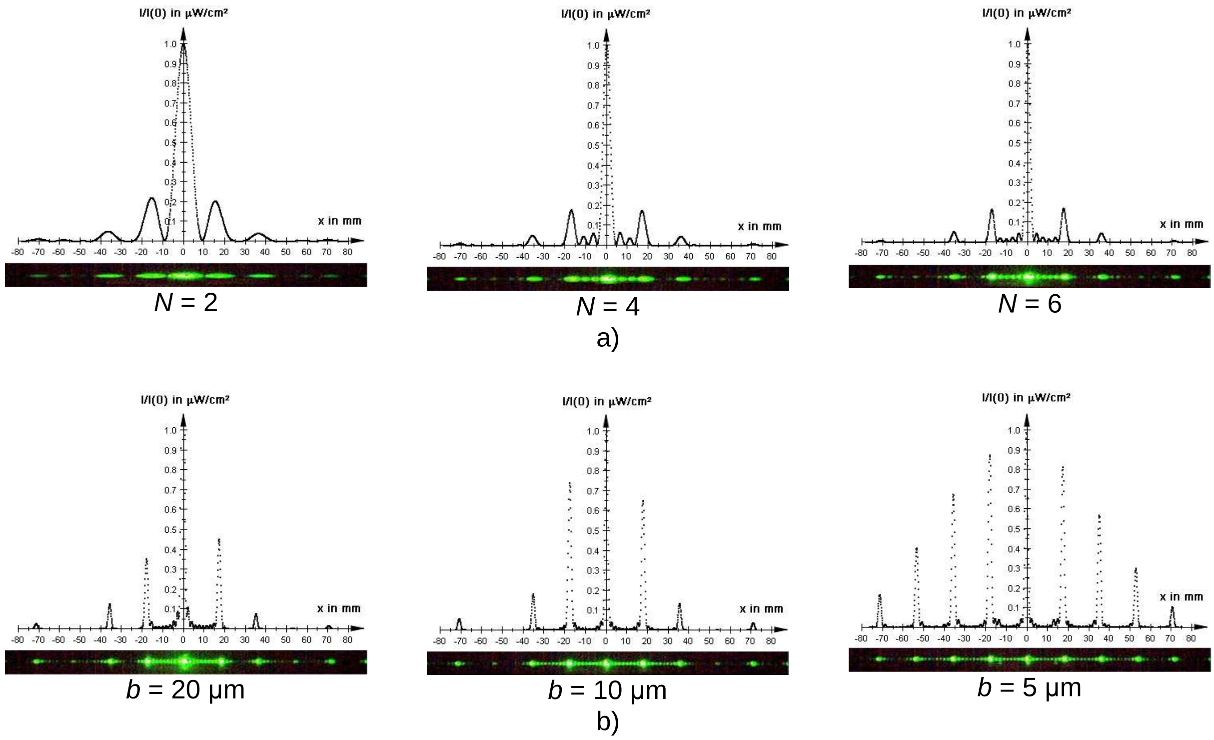
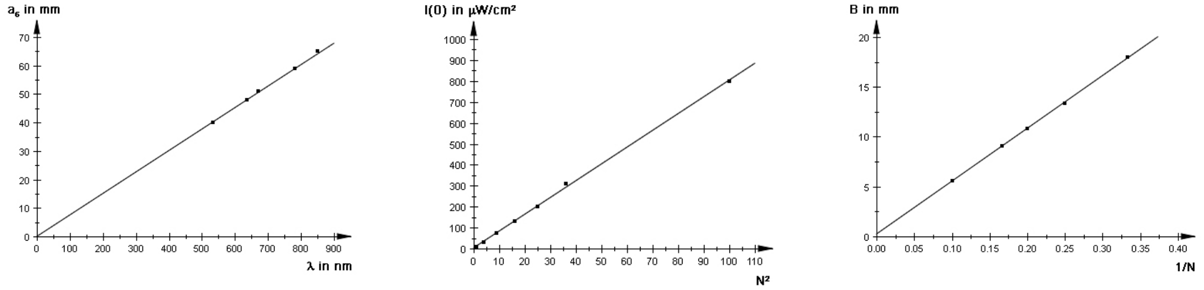


Figure 6. a) λ = 532 nm, b = 20 µm, d = 30 µm. Change of relative intensity distribution I/I(0) and diffraction pattern for increasing slit number N.
b) λ = 532 nm, N = 10, d = 30 µm. Change of relative intensity distribution I/I(0) and diffraction pattern for decreasing slit width b.

3.4 Further investigations with the intensity distribution of a grating

As a first series of studies we want to investigate the influence of parameter wavelength λ on diffraction. As an example we measured the distance a_6 of the maximum *n* = 6 from the central maximum (figure 7a). Measured data fit very well the theoretical prediction $a_6(\lambda) = 6e\lambda/d$.
As a second series of studies we want to investigate the property of central maximum. From formula 2 we expect that the intensity *I(0)* varies with the slit number *N* like $I(0) \sim N^2$, which is well documented by figure 7b. From theory we expect also that the width *B* of the central maximum vary with the slit number *N* like $B \sim 1/N$, again this is well confirmed in figure 7c.



a) b) c)

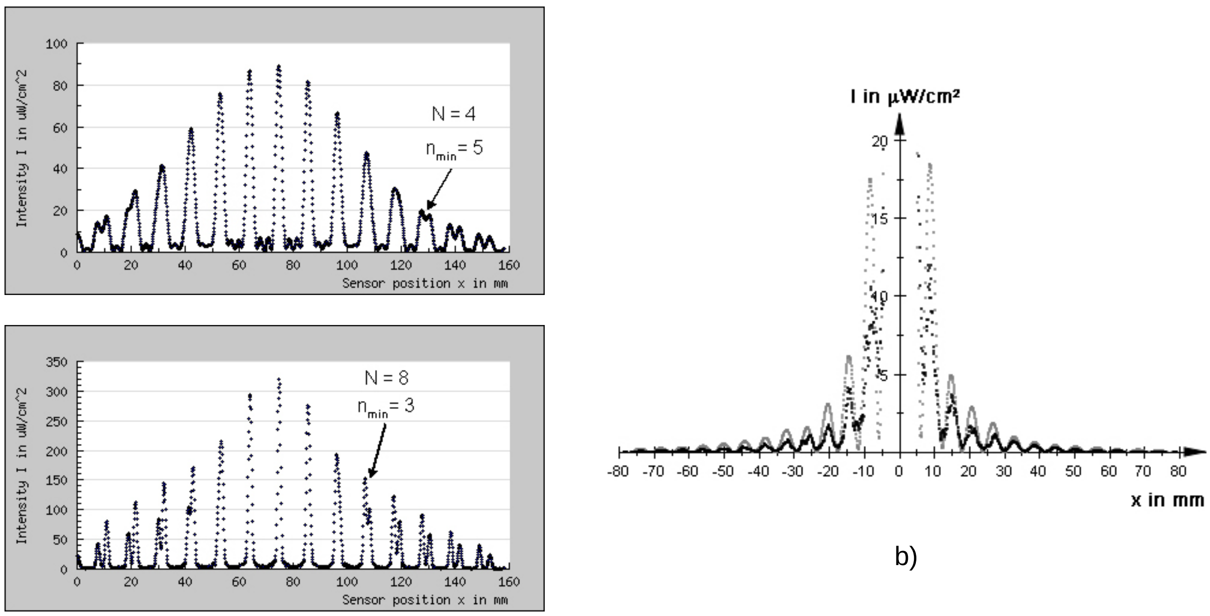
Figure 7. a) N = 10, b = 20 μm, d = 80 μm. Distance a_6 between maximum of order n = 6 and central maximum versus wavelength λ. Comparison between measured (squares) and theoretical data (line).
b) λ = 532 nm, b = 20 μm, d = 80 μm. Intensity I(0) of central maximum versus slit number N. Proof of I(0) ~ N^2 for measured data (squares) and regression line.
c) λ = 532 nm, b = 10 μm, d = 20 μm. Width B of central maximum versus slit number N. Proof of B ~ 1/N for measured data (squares) and regression line.

The three experimental results are fundamental to understanding the use and action of a grating in spectroscopy (resolution of light into different wavelengths and separation of two different wavelengths).

3.5 Resolving power of a grating and Babinet´s principle

In figure 8a we deal with the resolving power A of N slits. Due to the selected pair of laser diodes (λ_1 = 635 nm, λ_2 = 670 nm) we find a theoretical and constant resolution $A_{\text{theo}} = \lambda/\Delta\lambda$ = 635 nm/35 nm ≈ 19, which is equal to the product $n_{\min}N$ ($n_{\min}$ is minimal order to resolve the main maxima of two wavelengths). Therefore, if we increase the slit number N, the minimal order $n_{\min}$ decreases. The experimentally determined resolving power is $A_{exp} = 5\cdot 4 = 20$ for N = 4 and $A_{exp} = 3\cdot 8 = 24$ for N = 8.

In figure 8b we compare the intensity distribution of a single slit and a wire of the same width b. One can see that Babinets principle is confirmed, because the maxima and minima of slit and wire coincide.



a) b)

Figure 8. a) λ_1 = 635 nm, λ_2 = 670 nm, b = 5 μm, d = 60 μm. Intensity I versus sensor position x (diagrams from laboratory website) for increasing slit number N = 4 to N = 8. Decreasing order n_{min} (arrows) for resolved wavelengths. b) Comparison between measured intensity distribution of a slit (grey) and a wire (black) with the same width b = 90 μm (height of central maximum is not shown).

4. Concluding remarks

We designed this and all other RCLs such that the user can vary technical parameters (wavelength, diffracting object, detection type) like in a real experiment and that from a distance the user can follow in real time via webcams – as authentic as possible – how he or she is experimenting. The added value of this experiment “Diffraction and Interference” as an RCL experiment is the following:

- due to the fact of 157 diffracting objects many different measurements and investigations on different research levels are possible.
- electron lithographically produced diffracting objects achieve a contrast rich intensity pattern and allow one to consider limiting cases like an ideal grating.
- one can collect pretty good experimental data in a relatively short time for further experimental analysis and for theoretical modelling.
- the user can choose from among different techniques of measurement the best one for a given problem
- in the experiment a nearly continuous transition between qualitative, half quantitative and quantitative consideration of diffraction is possible.
- the user can exercise experimental skills, formulate hypotheses and plan a research measuring program besides dealing with pure physics.
- an individual user or a group of students can establish their own research questions and organize their own measuring program.

In addition we offer in the RCL menu item “Theory” a very comprehensive introduction into waves and superposition of waves. For different levels of teaching and learning we tabulate formulas for single, double and multiple slit and derive the formula for a multiple slit with and without using Fourier-Transformation. In the menu item “Material” the interested teacher will find a link to an extensive teaching sequence and additional materials (in German). We consider this RCL as well suited to catalyze a more autonomous learning in upper secondary school, to support experimental self study by students and to improve demonstration of diffraction in lectures at university.

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