83. Do-it-yourself Spectrometer

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I. Introduction

A spectrometer is a device used to measure properties of light over a certain range of wavelengths. A typical application is the separation of initially overlapping spectral lines from various light sources. There are two basic types of spectrometers: those which separate the light by means of a prism, and those which separate the light by means of a grating. We will investigate the latter in this experiment. For the theory behind a grating spectrometer, please consult the introductory section of lab experiment 15.

A very basic setup will be developed in what follows. The working principle of the grating spectrometer relies on the optical diffraction of light at a grating (called diffraction grating). The light from any light source (e.g. sun, light bulb, LED, ...) passes through a narrow slit at the entrance. The alignment of the slit corresponds to the alignment of the lines of the diffraction grating. By observing the interfering light after the grating, the spectral decomposed light can be investigated.

II. Building Instructions

Disclaimer: Make sure to take note of any information concerning the CD-type you are using (e.g. CD-R/CD-ROM, storage capacity,...) before you start! Be aware that the CD must be cut for the purpose of this experiment, thus all information on it will be lost.

Note about DVDs: It is also possible to use a DVD instead of a CD. However, the grating constant is about a factor of 2 larger (smaller spacing between the lines). This means the diffraction angles are much larger, and images can only be recorded with wide-angle objectives on the camera. Some smartphones already have this built-in, but others might not.

There are plenty of resources on the web for homemade grating spectrometers based on CDs. Please feel free to consult any sources of your choice as complementary reference. The finished product needs to meet the following requirements:

- Light needs to enter through a slit (<< 1 mm)
- It needs to pass through a grating (a piece of a CD, foil removed)
- It needs to finally be able to enter the camera of your smartphone in a reproducible manner (same position for all measurements)
- With the finished product you should be able to take photos of the slit with the diffraction pattern clearly visible and oriented parallel to the slit

1. Materials

- An old CD.
- Flat cardboard pieces. *Dark and non-reflective materials will yield better results!*
- Scissors/cutter
- Strong tape
- Two razor blades

- Optional:
  - Aluminum foil

There is a step-by-step instruction of how to build the spectrometer in the appendix A. If you experience problems during the assembly, please inform the supervising assistant and ask for help.

III. Tasks

In all following tasks in which you are required to use your own device, you are expected to take photos of the diffraction pattern while pressing your smartphone camera against the CD-side for best results.

In post-processing you can use any photo-editing program, imtools() from Matlab's Image Processing Toolbox or alternatively Power-Point to extract the individual distances in the pictures (in pixels) and scale them accordingly.

Since you are going to do most calculations at least twice, it is helpful to create functions for the most important calculations in the programming environment of your choice (Matlab/Python/Mathematica/Excel/...)

1. Grating constant of the CD

Design a theoretical experiment to measure the grating constant of the CD used to build the spectrometer. Assume that you have a red laser pointer of known wavelength $\lambda_{laser} = (650 \pm 10)$ nm and the average distance of the 1_{st} order diffraction maxima from the central maximum on the screen is $x_{avg} = (14.0 \pm 0.1)$ cm. The distance between the CD and the screen where the diffraction image is recorded is $D = (29.5 \pm 0.1)$ cm.

a) Write down the equation that defines the position of the diffraction maxima. Explain the meaning of the variables. You may find the manual for lab experiment 15 "Wavelength measurement with a grating", Section 1 "Basics", useful.

b) Evaluate the CD grating constant for given values and its uncertainty using the Gauss Method you learned about in the complementary lecture. Write the result as $(g \pm \Delta g)$ μm.

c) Estimate grating constant of the CD that you use in your spectrometer. If you do not have a monochromatic light source at hand, you can visually select a position from within the diffraction pattern you get for sunlight. Using a reference sheet with annotated wavelengths (as the one used in the task below), you should be able to retrieve reasonable wavelength values.

d) What is the error of your estimate? How does your result compare to the literature value for your CD/DVD-type? (Use this source as a reference: `https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5547333`. You can access it using the ETH VPN connection. Just don't forget to cite it in your report.)

e) What causes the error and how would you modify your setup to decrease the error?

2. Calibration

In order to extract the numerical values of wavelengths corresponding to different parts (colors) of the spectra, you will need to calibrate your device first.

One can use similar method as used for the He-spectrum in experiment 15. Your scale is given by e.g. your slit-length or the width of your spectrometer's front-face.

Alternatively, it is also possible to calibrate the spectrometer without referring to physical distances, by finding directly a scaling factor using one known wavelength (laser pointer or characteristic line in sunlight spectrum) and a corresponding distance in the picture.

For the grating constant, if you are perfectly sure of your CD-type, you may use the literature value for your calculations. Otherwise it is safer to use your own result.

3. Different sources of light

Now you can start using the spectrometer for wavelength measurements.

a) Which types of different light sources exist and how do they differ? Which ones do you have access to?

b) Which type of light source does a computer screen use? How come the colors on a computer screen look so realistic despite using only parts of the spectrum?

c) Follow the link: `https://www.ledr.com/colours/multi.htm` to display single color blocks on your computer screen. Point spectrometer at the monitor of your PC displaying white, magenta, grey, blue, cyan. Take pictures of each color block, define the wavelength range(s) you observe and compare it with a picture of the sunlight-spectrum.

d) Try to find at least two other light-sources except sunlight (the greater the difference compared to sunlight, the better), take a picture of them through your spectrometer and categorize them based on your answers above. Estimate their wavelengths/wavelength range.

e) In the lab experiment 15 there were two light sources, which you probably cannot find at home. Which type are they? What would the corresponding spectrum look like? Mark the expected position of the spectrum lines directly on the pictures from the sunlight taken in the previous task and screen of the PC (diffraction picture of what color is suitable for this purpose?).

4. Fraunhofer lines

The observation and correct interpretation of Fraunhofer lines (first seen in the early 19th century) was an important milestone toward modern spectroscopy. The underlying concept is used in all types of research up to this day.

a) Explain, what are the Fraunhofer lines and what causes their existence.

b) Can you observe them in your spectrum? You will probably not be able to see them very well. Explain, what could be the possible reasons for this.

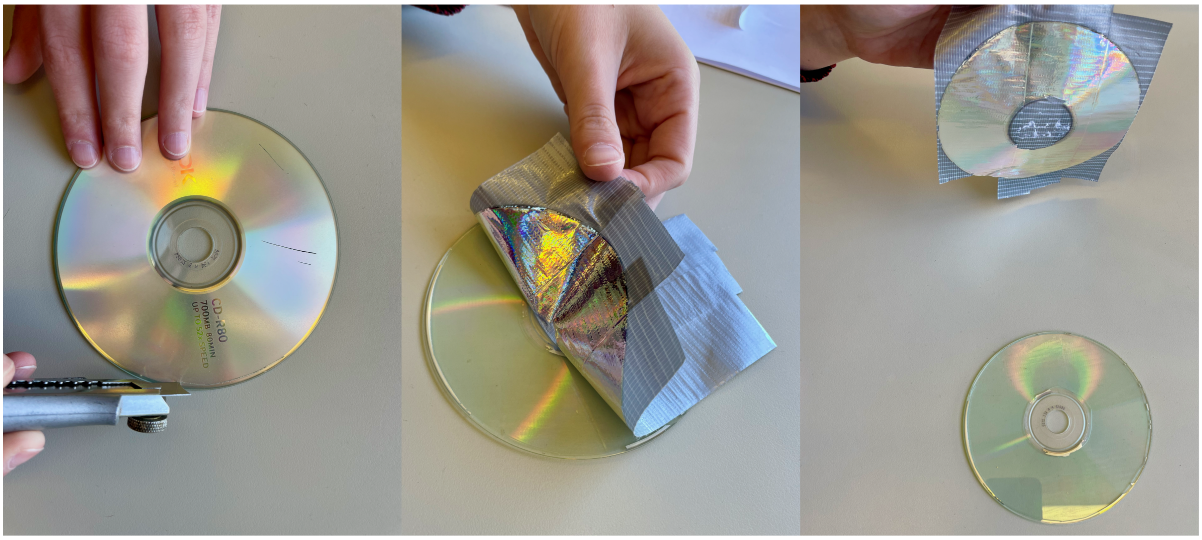
c) Draw Fraunhofer lines on top of the spectrum that you recorded and, for each line, specify which element absorbs at that specific wavelength. You can use as a reference data given here: `https://ap.phys.ethz.ch/WeitereDoks/HinweiseEichkurvenETC/24_Foto_Spektraltafel`

d) Explain how you could improve the spectrometer in order to detect the Fraunhofer lines.

A Step-by-step building instructions

This section contains an illustrated step-by-step instruction on how to build a spectrometer.

1. Prepare the CD



The goal is to remove the silver foil from the CD and reveal the transparent part with the tiny grooves that will act as a diffraction grating. In order to do that:

- cut through the silver foil along the outer and inner edges. You do not to cut deep, a shallow scratch will do,
- stick a few strips of strong duct tape to the side of the CD covered by the silver foil,
- peel the tape together with the foil from the CD.

After performing the above steps, you should be left with the transparent CD.

2. Build a tube

The dimensions of the tube (box) do not affect the results significantly. You can pick any reasonable shape and size. However, the material used is of importance, especially the inner surface - ideally it should not reflect light and should be rather dark.

We demonstrate this step using a piece of cardboard:

- cut a rectangle,
- divide the rectangle into 4 equal parts and cut them (partially or completely),
- fold the cardboard, forming a box with open ends. Use duct tape to hold the pieces together,
- cover one side of the tube with your hand and look through the other end - if you can see light entering the box from any side, add some more duct tape to block it.

Now the box that will constitute a base for the spectrometer is ready! Note: Of course you can already start with a cardboard box / cylinder, which might make some of the above mentioned steps obsolete.

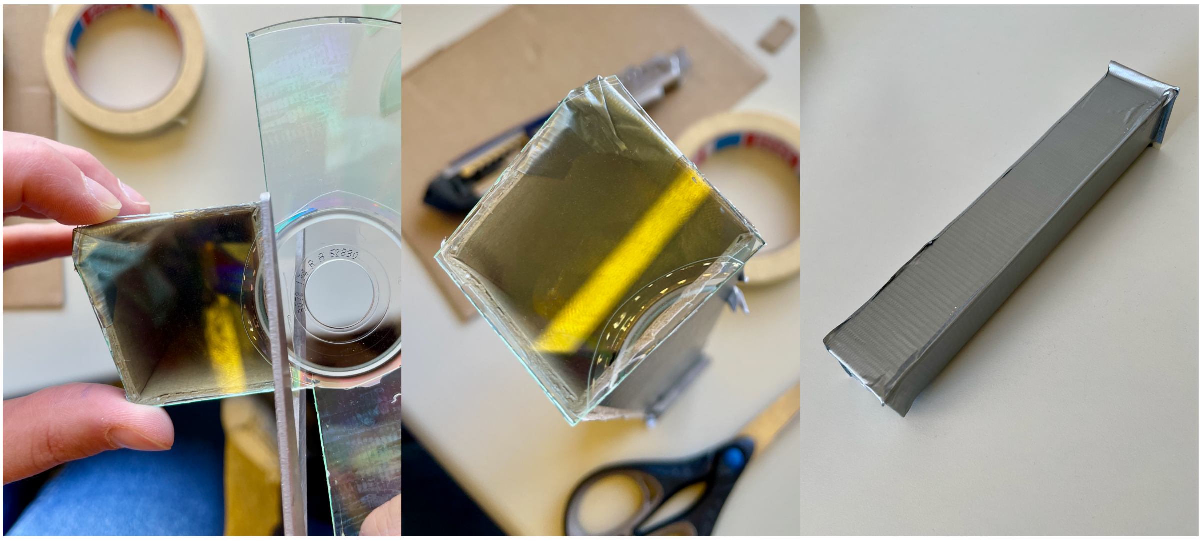
3. Create a slit

This is the step that requires the most precision, as we need to create a slit with smooth edges which are parallel to each other, and which are separated by about 0.1 mm. Perform the following steps:

- Cut a square from a cardboard that is approximately the size of the opening in the tube,
- cut a rectangular opening in this square (approximately 1x2 cm),
- carefully attach one of the razor blades to the cardboard using tape. It should cover about half of the opening. We may need to move the blade later on, so it is advisable not to attach it too firmly yet.
- Take the second blade, and put it next to the first blade. It should be very close such that there is a tiny gap between them. A good practice is to take 2-3 sheets of paper and put them between the blades as separator. Then, attached the second blade to the cardboard piece. This way we can make sure that the slit is parallel and sufficiently narrow.

The most tricky part is over. Keep in mind that you may have to repeat this step with different number of paper sheets in case the quality of pictures from the spectrometer is not satisfactory.

4. Assemble the spectrometer



The next step is to put all pieces together:

- Make sure that you know the direction of the grooves in the transparent CD you prepared earlier. Align them with one of the edges of the box and mark their direction on the box, so that later we know how to position the slit. The grooves on a CD are concentric circles.
- Cut a piece of the CD fitting the opening in the box. Either use scissors or a sharp knife. Keep in mind that the concentric grooves on the CD are more parallel the further away from the center of the CD they are. Straight grooves deliver better results than curved grooves.
- Attach the CD piece to the box with tape (since we may still need to improve its position later, only fix it lightly).
- Tape the slit to the opposite end of the box, making sure that it is parallel to the grooves in the CD.

The spectrometer is almost ready. If you look through it at some source of light, either with bare eye or through the camera, you may already see some light spectra on both sides of the slit!

5. Adjustment

Finally, we want to make assure the best possible quality of pictures. There are a few factors to take into consideration:

- the overall contrast, brightness, noise level,
- wavelength measurement resolution,
- geometry of the spectra.

In order to assess the performance in each of these categories, take a picture of the sunlight spectrum and a white LED screen (for the latter one, make sure the room is otherwise completely dark).

The first two points can be addressed looking at the LED screen picture. If you can see bright, narrow, clearly separated red, green and blue lines/regions, then you have managed to build a high-quality slit! Otherwise:

- If the colors blend together: try reducing the width of the slit. Also, pay attention to a parallel positioning of the blades.
- If the lines are very faint, or you cannot see them at all: first try making the slit wider. If this does not help, it is possible that your CD is not cleared well.

The last point can be best checked with the sunlight spectrum. Ideally, you should see two colored bands on both sides of the slit - their edges should form rectangles, rather than parallelograms with angles different from 90 degrees. If in your pictures you see something visibly different from right angles, try rotating either the CD or the slit. In case you only see very narrow lines instead of rectangles, it is likely that the slit is rotated by 90 degrees with respect to the grating.

6. Final touch

When you are confident that your spectrometer can provide good quality pictures, you can add more tape to the box, slit and CD to minimize the amount of parasitic light entering the box through any way other than the slit.

Usually it makes sense to position the spectra on the diagonal of the picture - like that you gain a bit of extra space, which may allow to see the far-red part of the spectrum, which otherwise could be cropped.

In order to achieve good measurement precision, try to find a way to attach the camera to the box: you could build a clamp to hold it in place, or tape a phone case to the box, or even tape the phone directly to the spectrometer. The important part is to make sure all pictures are taken from exactly the same position and angle.