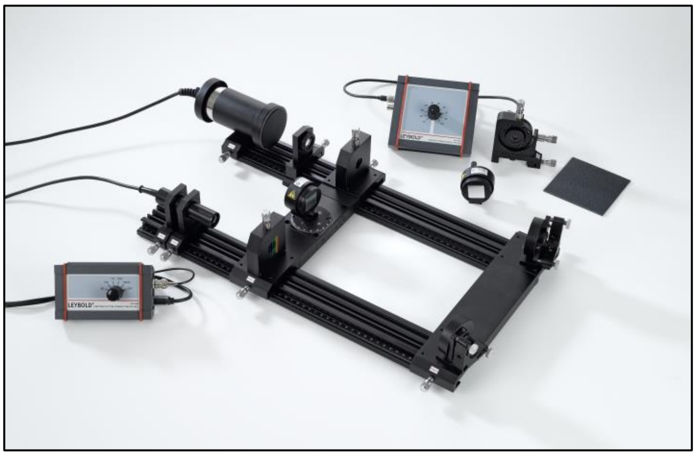

Spectral analysis

Objects of the experiment

- Investigation of the principle of gratings
- Principles of spectrograph and Czerny-Turner monochromator
- Investigation of a spectral lamp and line spectrum

Principles

a) Principle of diffraction

Diffraction is the bending of waves as they pass by some objects or through an aperture. The phenomenon of diffraction can be understood using Huygens's principle which states that:

Every unobstructed point on a wavefront will act a source of secondary spherical waves. The new wavefront is the surface tangent to all the secondary spherical waves.

According to Huygens's principle, light waves incident on two slits will spread out and exhibit an interference pattern in the region beyond. The pattern is called a diffraction pattern.

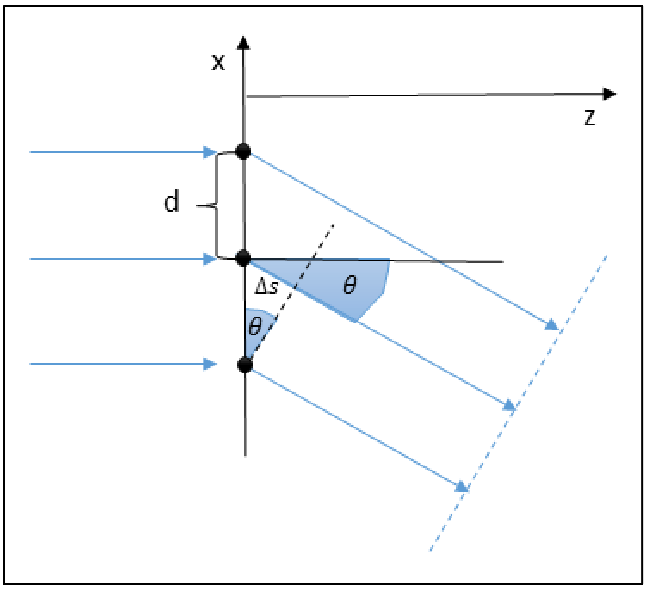

Fig. 1: Principle of diffraction. Calculating the optical path difference Δs.

A diffraction grating is a collection of reflecting (or transmitting) elements separated by a distance comparable to the wavelength of light under study, as shown in Fig. 1. It may be thought of as a collection of diffracting elements, such as a pattern of transparent slits in an opaque screen, or a collection of reflecting grooves on a substrate. Upon diffraction, an electromagnetic wave incident on a grating will have its electric field amplitude, or phase, or both, modified in a predictable manner, due to the periodic variation in refractive index in the region near the surface of the grating.

To calculate the diffraction of a parallel wave through a slit, assume that there are *N* regularly ordered sets of oscillators with the distance *d* to each other. If a parallel wave hits the slit, all oscillators begin to oscillate at the same time.

Consider that under a special angle θ the waves have to travel different distances. The optical path difference Δs is illustrated in Fig. 1 and can be calculated with the following formula:

$$\Delta s = d \cdot \sin\theta$$

This causes a phase difference of

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta s = \frac{2\pi}{\lambda} d \cdot \sin\theta$$

of two neighbored waves. When this distance is equal to an integer number m of wavelengths λ of the incident light, the two beams are in phase and will exhibit constructive interference by displaying a series of bright regions on the screen. These interference maxima are given by:

$$d \sin\theta = m\lambda, \quad m = 0, \pm 1, \pm 2, \ldots$$

where λ is the wavelength, d is the grating spacing, and m is an integer called the order number. If the path difference between adjacent beams is $\left(m + \frac{1}{2}\right)\lambda$, then destructive interference will result in dark regions, or interference minima, on the screen. The zero-order beam $m = 0$ is a continuation of the incident beam. Hence the measurement of the angle, together with the order number m, gives the ratio λ/d, and if either λ or d is known, the other can be calculated.

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The intensity of the diffracted light of a diffraction grating is given by the following formula:

$$I(\theta) = I_o \frac{\sin^2\left[\pi\left(\frac{b}{\lambda}\right)\sin\theta\right]}{\left[\pi\left(\frac{b}{\lambda}\right)\sin\theta\right]^2} \cdot \frac{\sin^2\left[N\pi\left(\frac{d}{\lambda}\right)\sin\theta\right]}{\sin^2\left[\pi\left(\frac{d}{\lambda}\right)\sin\theta\right]}$$

b is the width of a single slit, d is the distance between two slits. N is the number of slits. θ is the angular distance from the center of the diffraction pattern and λ is the wavelength of the light.

The first factor represents the diffraction of a single slit and the second factor the interference between N slits.

b) Reflection gratings

Gratings can be either transmissive or reflective gratings, with transparent slits or a reflecting structure. Despite the regular structure of the grating, each slit can have a microstructure. Here we assume that the grating is sawtooth shaped. This introduces a blaze angle and in effect, the intensity distribution of the reflection will be changed to increase the light going to the +1 diffraction order and reducing light in all the other diffraction orders.

For the examination of a reflection grating we introduce two normals: the groove normal, which is orthogonal to the reflective surface, and the grating normal, which is orthogonal to the base plane, as shown in Fig. 2.

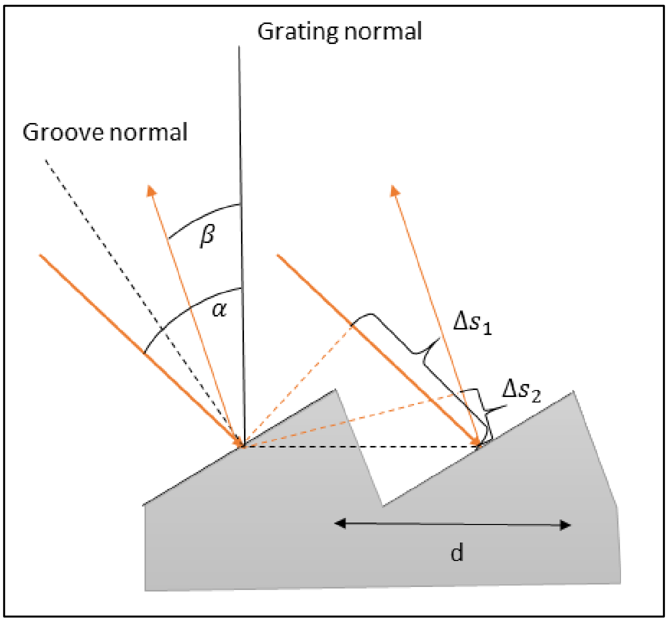

Fig. 2: The directions of diffracted orders for a reflective diffraction grating. Incident and reflected light are on the same side of the grating normal.

If the parallel light incidents at the angle α to the groove normal and is reflected at the angle β a path way difference Δs occurs.

The path way difference is

$$\Delta s = \Delta s_1 + \Delta s_2 = d(\sin\alpha + \sin\beta)$$

With the convention of positive β as shown in Fig 2.

These leads to the general grating equation

$$\frac{n\lambda}{d} = \sin\alpha + \sin\beta$$

.

c) Czerny-Turner monochromator

The standard Czerny-Turner design is shown in Fig. 3. A divergent wavefront from the entrance slit S_1 is collimated by spherical mirror M_1 and then diffracted in the tangential plane by the grating G. The light is then focused by spherical mirror M_2 onto the photodetector P.

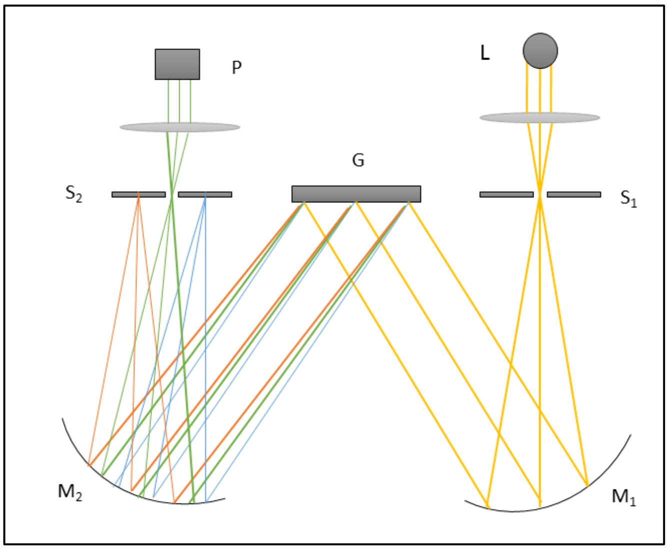

Fig. 3: Principle of a Czerny-Turner monochromator.

In Fig. 3 is the principle of a Czerny-Turner monochromator. This arrangement is called W-type.

The first spherical mirror M_1 is so placed, that its focus is at the first slit. The reflected wave is now parallel and incident the reflection grating at an angle α. Due to the grating equation different wavelength are reflected at different angles. The different wavelengths incident parallel at the second spherical mirror and are focused to the second slit plane. The focus on the second slit plane depends on the incident angle at the second mirror. Hence, only a small width of wavelength can pass through the slit. By turning the grating a special wavelength can be selected and it is called a monochromator.

d) Spectral resolution

The resolving power R of a diffraction grating is at best an impractical, theoretical concept and is given by:

$$R = \frac{\lambda}{\Delta\lambda}$$

where $\Delta\lambda$ is the difference in wavelength between two spectral lines of equal intensity. Resolution is the ultimate ability of an instrument to separate two spectral lines. By the Raleigh criterion, two peaks are considered resolved when the maximum of one falls on the first minimum of the other. It can be shown that:

$$R = \frac{\lambda}{\Delta\lambda} = knW_g = kN$$

where λ, the central wavelength to be resolved; W_g, the illuminated width of the grating; and N, the total number of grooves on the illuminated width of the grating.

e) Spectral lamp

In general there are three classes of lamps: incandescent, discharge, and solid-state lamps. Incandescent lamps produce light by heating a filament until it glows. Discharge lamps produce light by ionizing a gas through electric discharge inside the lamp. Solid-state lamps use a phenomenon called electroluminescence to convert electrical energy directly to light.

Spectral lamps are discharge lamps that produce light by passing an electric current through a gas that emits light when ionized by the current. An auxiliary device known as a ballast supplies voltage to the lamp's electrodes, which have been coated with a mixture of alkaline earth oxides to enhance electron emission. Two general categories of discharge lamps are used to provide illumination: high-intensity discharge and fluorescent lamps.

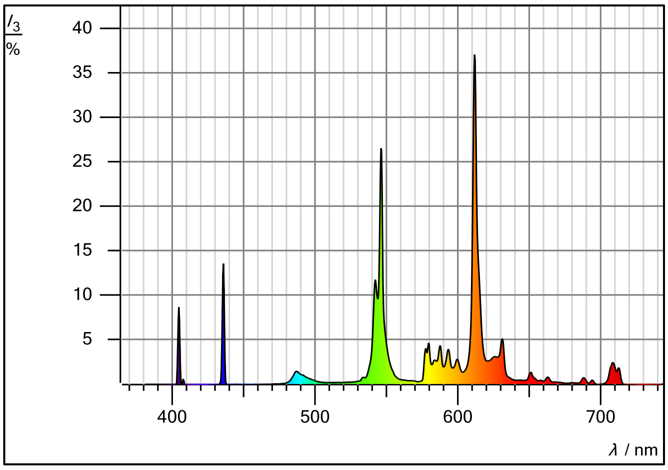

Fig. 4: Spectrum of a mercury lamp.

The fluorescent lamp is a gas discharge source that contains mercury vapor at low pressure, with a small amount of inert gas for starting. Once an arc is established, the mercury vapor emits ultraviolet radiation. Fluorescent powders (phosphors) coating the inner walls of the glass bulb respond to this ultraviolet radiation by emitting wavelengths in the visible region of the spectrum. In this experiment a fluorescent lamp is used and will be investigated.

Experiments

To visualize and measure the properties of a Czerny-Turner monochromator the following experiments are presented.

Setup:

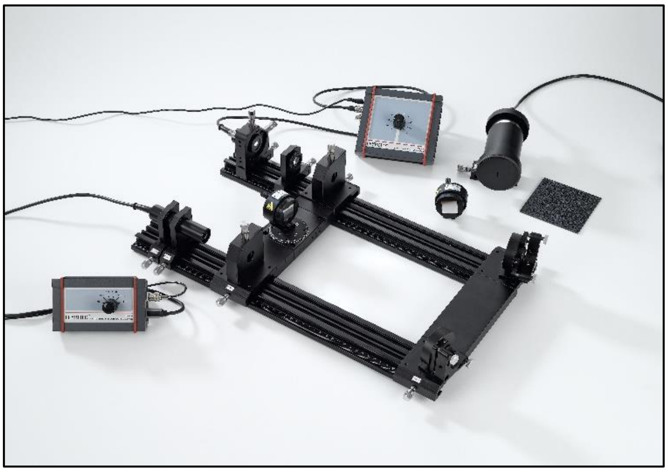

Fig. 5: Complete setup of this experiment

Setup on Bench:

1 Plano-Convex lens f = 40 mm, C25 mount ...474 5216
1 Biconvex Lens f = 20 mm, C25-T Mount 474 5218
1 Spectrometer Mirror Assembly 474 177
1 Spectrometer Grating Assembly 474 178
1 Photodetector signal conditioning box 474 306
1 SiPIN photodetector 474 108
1 Digital multimeter DMM 121 ....531 173
1 Screened cable, BNC/4 mm 575 24
1 Adaptive Power Supply 474 301
1 LED Lamp, White 474 5411
2 Profile rail, 500 mm 474 5442
2 Mounting Plate C25 with Carrier 20 mm 474 209
1 Adjustment holder, 4 axes, with stop ang 474 2112

At first, start with the two profile rails 500 mm and place them parallel to each other. Mount the Spectrometer Grating Assembly (474 178) and then the Spectrometer Mirror Assembly (474 177) on the profile rails, as shown in Fig. 5 and 6. These two Assemblies should be mounted so that the mirrors and the grating faces each other. Note that the rotary screw of the grating shows to the outside. Do not finally tighten the screws of the holders until fine tuning.

Place one of the grating in the grating holder at the Spectrometer Grating Assembly. Be careful to not touch the gratings surface. To fix the grating in the holder there is a little screw and a screwdriver provided.

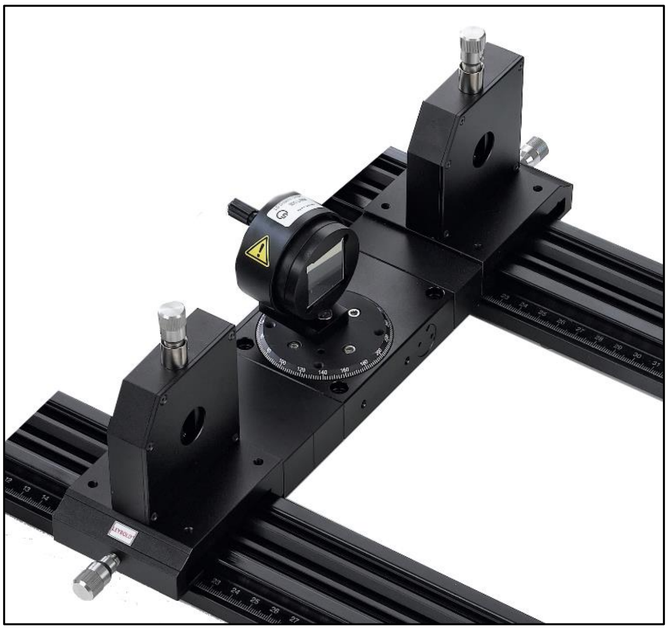

Fig. 6: Spectrometer Mirror Assembly mounted on the profile rails.

Fig. 7: Spectrometer Mirror Assembly mounted at the end of the profile rails.

At next step place the LED Lamp with the adjustment holder and the Plano-Convex lens f = 40 mm with C25 mount in front of the first slit, as shown in Fig. 7.

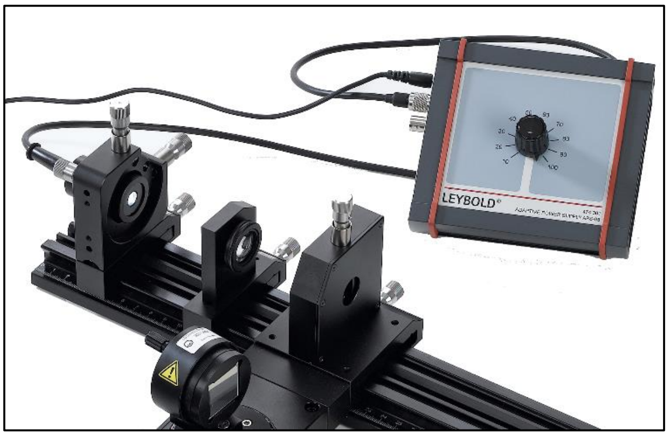

Fig. 8: LED Lamp and lens f = 40 mm placed before the first slit.

Connect the LED Lamp with the adaptive power supply. The screws of the holder are not tighten either.

Now place the photodetector and the Biconvex Lens f = 20 mm with C25-T Mount behind the second slit, as shown in Fig. 8. This lens with a protective tube should be placed directly in front of the photodetector to image the slit onto the photodiode.

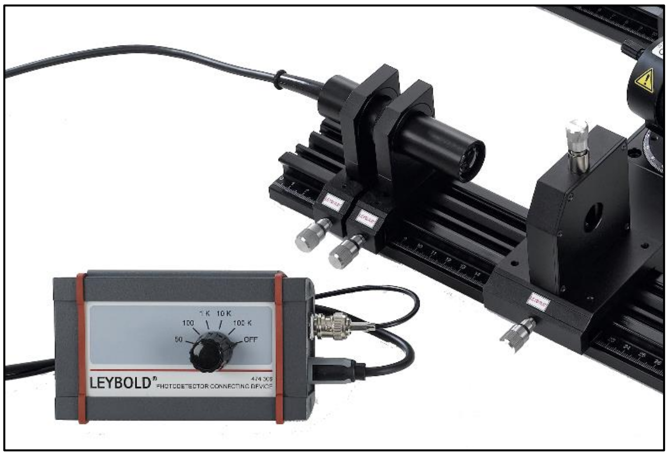

Fig. 9: Photodetector and Biconvex Lens f = 20 mm behind the second slit.

Connect the photodetector with the photodetector signal conditioning box and with the digital multimeter via BNC cable. Run the multimeter in voltage mode and set the controller of the conditioning box so that the output voltage is around about a few hundred mV. Note that the conditioning box runs with a 9 V battery so that this is the maximum output voltage.

At this point every element is mounted and is placed at a coarse position. For the fine tuning it is important to start with the first element in the row and move on element by element. After the adjustment of every element, tighten the screws of the holder.

For the following fine tuning it is better to dim the surrounding lights and use a white sheet of papers for the light path. Now turn the LED Lamp at a maximum intensity and open the first slit by turning the screw on the top. Slide the lamp and the lens so that first mirror is completely illuminated. Then tighten the screws of holder.

The mirrors at the Spectrometer Mirror Assembly are spherical mirrors, which can focus the light.

At this point there are two adjustments that should be done nearly parallel. Firstly, the screws at the mirrors holder can tilt the mirror plane in different directions. Turn the mirror plane of the first mirror so that the light beam illuminates the grating completely. Secondly, the distance between the slit and the mirror can focus the out coming light to infinity, if the slit is in the focus of mirror.

Therefore slide the Spectrometer Mirror Assembly so that the reflected light beam does not change its size by moving a white sheet of paper in the reflected beam.

The optimal situation is that the reflected light is focused to infinity and illuminates the whole grating.

Now that the grating is completely illuminated it is possible to adjust the grating. Therefore use the screws at the back of the grating holder and the turning screw of the rotary unit. Turn these screws in the way that the reflected diffraction maxima are visible at the second mirror. Note: Do not slide the assemblies any more. These should be adjusted in the steps before.

The next step is to adjust the second mirror. Turn only the screws to tilt the mirror plane so that the image of the first slit covers the entrance of the second slit, as shown in Fig. 10.

Fig. 10: Image of the first slit at the entrance of the second slit.

To find these images of the slits the best way is to use a white sheet of paper. Then open the second slit be tuning the screw on the top. Now turn the screw of the rotary unit of the grating so that one slit can pass through the second slit.

At the last step slide the photodetector and lens so that image of the slit covers the entrance of the photodetector.

A setup that worked is shown in Fig. 10. There are the distances of elements shown.

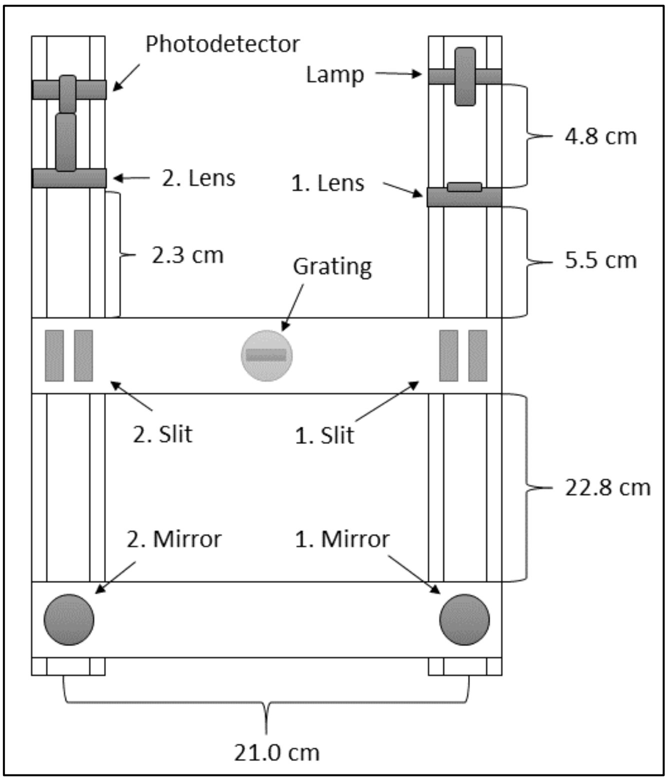

Fig. 11: Setup with distances of the elements.

Experiment 1:

To measure and determine the wavelength of an unknown light source it is necessary to calibrate this setup. Therefore we use a light source with known wavelength. In this experiment it is a mercury lamp.

Fig. 12: Calibration of the spectrometer.

Setup on Bench:

1	Plano-Convex lens f = 40 mm, C25 mount	...474 5216
1	Biconvex Lens f = 20 mm, C25-T Mount	.......474 5218
1	Spectrometer Mirror Assembly	.......474 177
1	Spectrometer Grating Assembly	.......474 178
1	Spectral Lamp with Slit and Power Supply	....474 5417
2	Profile rail, 500 mm	........474 5442

1 Mounting Plate C25 with Carrier 20 mm 474 209

Replace the adjustment holder and LED lamp with the spectral lamb. There are two different slits to place directly in front of the spectral lamb. Note the spectral lamb can be moved in the case so that the slit fits perfect at the end. Use the thinner slit for this experiment. It can take a few minutes until the spectral lamp reaches its maximum intensity.

Adjust the spectral lamp and lens again, so that the first mirror M_1 is completely illuminated. Note: Do not readjust the mirror or grating assembly!

Remove the photodetector and the second lens. In this experiment it is possible to look after the second slit directly with the eye in the light beam, because the intensity after the second slit is low enough.

Turn the grating with the screw at the grating holder so that a single spectral lines hit the second slit. To measure the angle there are two scales. The coarse scale is on the disk where the grating is mounted, the fine scale is on the turning screw. The steps on the disk are two degrees, on the turning screw in minutes. The angle is then the sum of both scales. Now measure the angles of the known lines: yellow, green, blue and violet.

Table 1: Measured angles to the spectral lines of mercury.

Line	θ	λ_{Lit} in nm
Yellow	16°58’	579
Green	17°40’	546
Blue	19°41’	436
Violet	20°12’	405

The measured angles and the literature value are shown in table 1. To fit this value it is necessary to convert the minutes into degrees: $1' = 1/60\,°$.

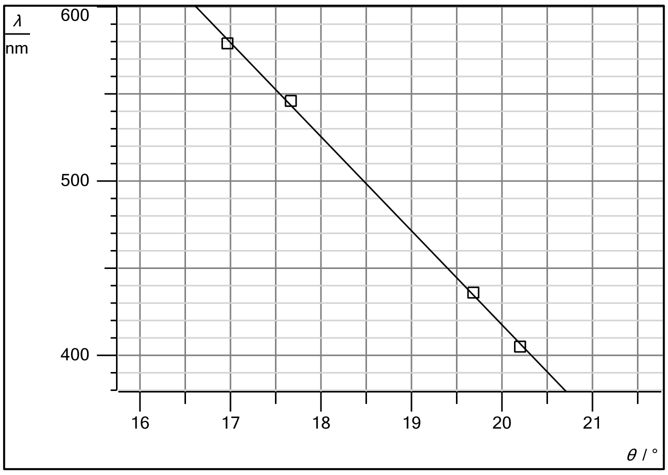

Fig. 13: Calibration fit of the 600 lines / mm grating.

The linear fit leads to the following equation:

$$\lambda(\theta) = -54.0\ \mathrm{nm}/° \cdot \theta + 1496.9\ \mathrm{nm}$$

Now it is possible to convert the measured angles of an unknown light source into wavelengths.

Experiment 2:

In this experiment the intensity of a white LED is investigated.

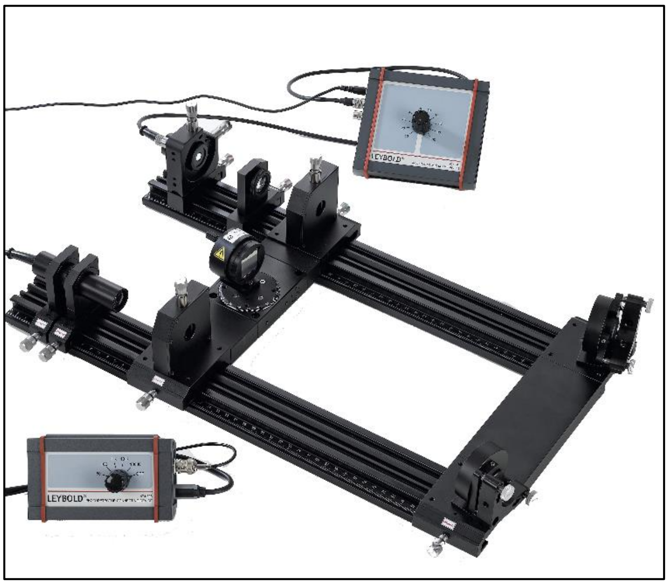

Fig. 14: Setup to measure the intensity distribution of a white LED lamp

Setup on Bench:

1 Plano-Convex lens f = 40 mm, C25 mount ... 474 5216
1 Biconvex Lens f = 20 mm, C25-T Mount 474 5218
1 Spectrometer Mirror Assembly 474 177
1 Spectrometer Grating Assembly 474 178
1 Photodetector signal conditioning box 474 306
1 SiPIN photodetector 474 108
1 Digital multimeter DMM 121 .... 531 173
1 Screened cable, BNC/4 mm 575 24
1 Adaptive Power Supply 474 301
1 LED Lamp, White 474 5411
2 Profile rail, 500 mm 474 5442
2 Mounting Plate C25 with Carrier 20 mm 474 209
1 Adjustment holder, 4 axes, with stop ang 474 2112

Replace the spectral lamp with the adjustment holder and LED lamp. Adjust the LED lamp and lens again, so that the first mirror M_1 is completely illuminated. Note: Do not readjust the mirror or grating assembly!

Mount the photodetector and lens behind the second lens so that image of the slit covers the entrance of the photodetector.

Connect the photodetector with the photodetector signal conditioning box and with the digital multimeter via BNC cable. Run the multimeter in voltage mode and set the controller of the conditioning box so that the output voltage is around about a few hundred mV. Note that the conditioning box runs with a 9 V battery so that this is the maximum output voltage. In this experiment the intensity is very low so that maximum amplification is used.

Now measure the intensities of the whole spectrum by turning the rotary unit by only a few minutes.

Results:

At first calibrate the measured angles with the calibration done in the first experiment.

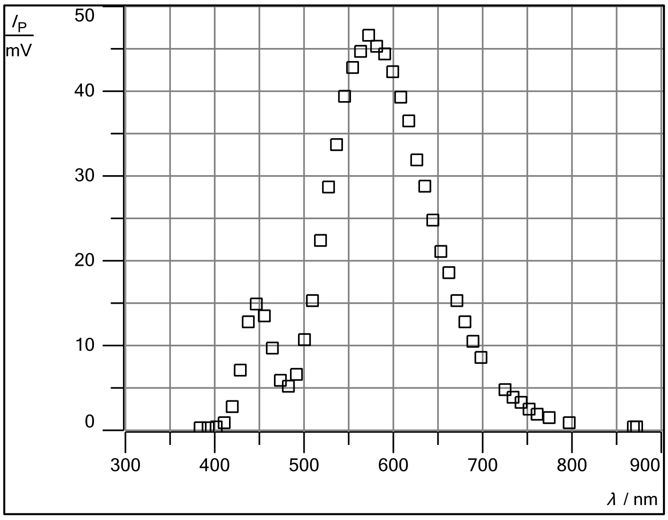

Fig. 15: Intensity distribution of a white LED.

In Fig 15. is the intensity distribution of a white LED lamp shown. The small peak is at 445 nm and it is blue part of white LED lamp. The large peak at about 570 nm is the superposition of the green and red part of the LED.

Experiment 3:

In this experiment the spectral properties of a spectral filter (acrylic absorption filter) is investigated.

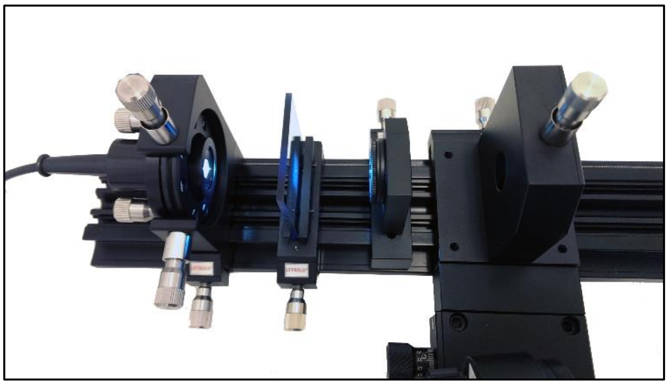

Fig. 16: Measuring the spectral properties of an acrylic absorption filter.

The setup on the bench is similar to the experiment 2. In addition to that setup place the filter plate holder with the acrylic absorption filter behind the white LED lamp.

Measure the intensities of the spectrum the same way as in experiment 2.

Results:

The reference intensity without filter was measured in experiment 2 and is shown as red dots in Fig. 17. The measured intensities with an acrylic absorption filter are the blue dots in Fig. 17.

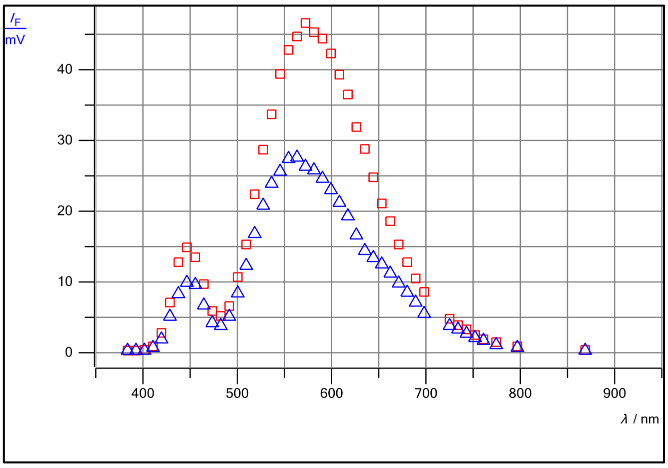

Fig. 17: Intensity distribution of the white LED with filter (blue) and without filter (red).

To calculate the transmittance of the acrylic absorption filter the following formula:

$$T = \frac{I_0}{I_F}$$

where I_F is the intensity with the filter.

The transmittance is shown in Fig. 18.

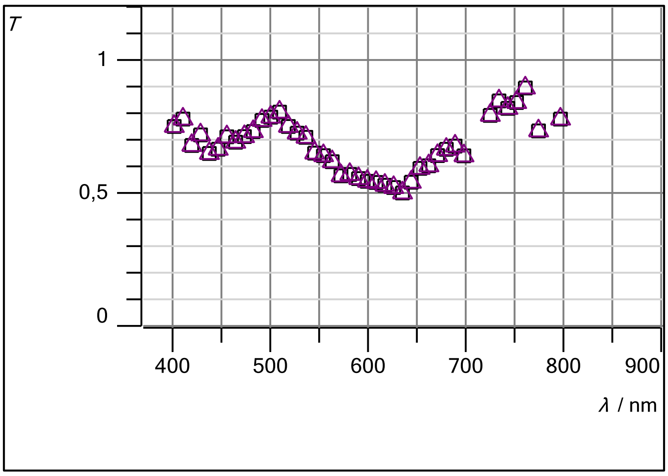

Fig. 18: Measured transmittance of the acrylic absorption filter.

The minimum transmittance is at about 635 nm. In the attachments the transmittance of this optical filters is completely measured with a high resolution spectrometer.

The experiments 1-3 can be repeated with the other grating.

Experiment 4:

In this experiment the spectral resolution of the spectrometer is investigated. Therefore use the same setup as in experiment 2.

This time we use both gratings. (600 lines/mm and 300 lines/mm).

For this experiment measure the width of a spectral line. Therefor turn the rotary unit so that the beginning edge of the line hits the slit and measure the angle. Repeat this for the ending edge of the line. The difference is the width of the line. Measure also the middle of the line.

Results:

Table 2: Measured the width of the spectral lines with 600 lines/mm.

Line	θ	$\Delta\theta$
Red 1	15°34'	6'
Red 2	16°19'	32'
Yellow	16°58'	26'
Green	17°40'	21'
Turquoise	18°42'	29'
Blue	19°41'	7'
Violet	20°12'	3'

The wavelengths can now be calculated with the calibration in experiment 1. $\Delta\lambda$ can be calibrated with the calibration as well. Note that $\Delta\theta$ is a difference so that the constant part of the calibration drops out.

The resolution of the spectrometer is then given by

$$R = \frac{\lambda}{\Delta\lambda}$$

Table 3: Resolution of the spectrometer with a 600 lines/mm grating.

Line	λ in nm	$\Delta\lambda$ in nm	R
Red 1	656.3	5.4	121
Red 2	615.8	28.8	21
Yellow	580.7	23.4	25
Green	542.9	18.9	29
Turquoise	487.1	26.1	19
Blue	434.0	6.3	69
Violet	406.1	2.7	150

This can be done exactly the same way with the 300 lines/mm grating.

Attachments

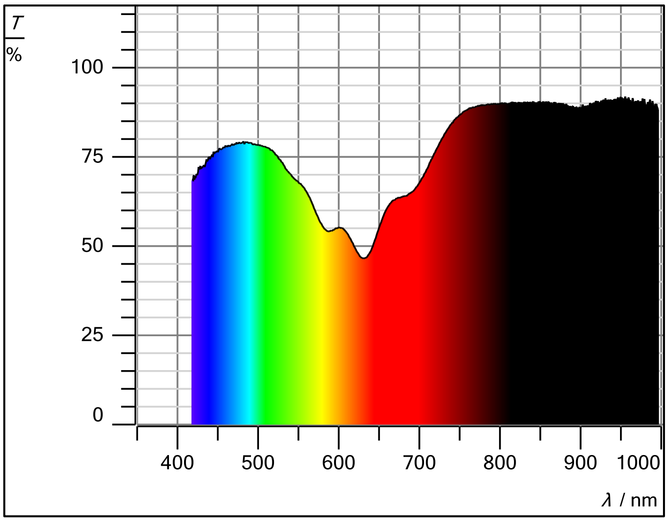

Fig. 19: Transmittance of the acrylic absorption filter.

Apparatus

1 Plano-Convex lens f = 40 mm, C25 mount 474 521
1 Biconvex Lens f = 20 mm, C25-T Mount 474 5218
1 Acrylic Absorption Filter 474 5211
1 Spectrometer Mirror Assembly 474 177
1 Spectrometer Grating Assembly 474 178
1 Filter Plate Holder 474 107
1 Photodetector signal conditioning box 474 306
1 SiPIN photodetector 474 108
1 Digital multimeter DMM 121 .... 531 173
1 Screened cable, BNC/4 mm 575 24
1 Adaptive Power Supply 474 301
1 LED Lamp, White 474 5411
1 Spectral Lamp with Slit and Power Supply ... 474 5417
2 Profile rail, 500 mm 474 5442
2 Mounting Plate C25 with Carrier 20 mm 474 209
1 Adjustment holder, 4 axes, with stop ang 474 2112
2 Transport and Storage Box #01 ...... 474 251
1 Manual Spectral analysis 474 7214