Spectrometer

Nanophotonics and Metrology Laboratory

Institute of Microengineering,

School of Engineering,

École Polytechnique Fédérale de Lausanne,

EPFL-STI-IMT-NAM

ELG 237

Station 11

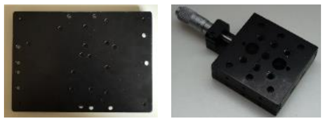
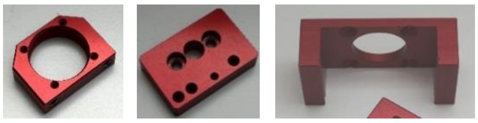
CH-1015 Lausanne

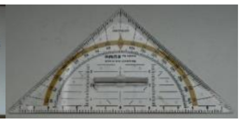
Web: http://nam.epfl.ch

Contact person: Dr. Karim Achouri,
Phone: +41 21 695 42 86,
E-mail: karim.achouri@epfl.ch

EPFL

List of material for the TP

1x board 1x linear stage	
1x camera holder (3 parts)	
1x camera	
1x source holder	
1x laser 1x halogen source **1x LED source**	
1x lens cap 1x slit cap	
1x 6 axis stage 1x adapter plate (red part)	
1x camera holder	

1 set of optical glass filters (9 pieces)	
1x grating (fragment of CD ROM)	
5x large screws with cap 4x small screws with cap	 
4x small screws (triangular head) 4x small plastic screws 6x large screws	  
3x Allen keys	
1x slotted screwdriver 1x screwdriver crosshead	 
4x small screws (triangular head) 4x small plastic screws 6x large screws	  
1x black cover	
1x ruler 1x triangle	 

1 Objective and overview

Spectroscopy is one of the most used techniques for sensing. Often light is sent onto an object and the reflected (or transmitted) light is analysed for its spectral composition. A grating spectrometer that uses a camera instead of a scanning photo detector has the advantage that the complete spectra is recorded at once, which allows short measurement times.

This practical work should introduce the following subjects to you:

- Understand the operation principle of a grating spectrometer
- Build a grating spectrometer and calibrate it
- Measure the spectra of the LED and a colour filter

To get this done you need to read the reference document provided.

2 Background

Camera

In our experiment, we use a pixelated camera. The pixels are arranged in a regular array that is produced at very high precision. The camera chip has 1600 x 1200 pixels and is 4.536mm x 3.416mm wide and large respectively. The pixel pitch is 2.835 microns in both directions (square). We can safely assume that there is no deviation of pixel position.

Laser source

Diffraction is easily observed with a laser. As a laser source, a **monomode laser diode** (model Opnext_Laserdiode-HL6354_EN) was chosen. The spectral properties are shown below. The width of a single peak is very narrow, below 0.2 nm FWHM. If no special measures are taken, lasers will have several modes. The spectral separation and spectral width are determined by the geometry of the laser resonator (Fabry Perot effect!). The laser resonator determines together with the laser active material the spectral properties of the laser. The pumping (electrically or optically) of the system gives its power generation properties.

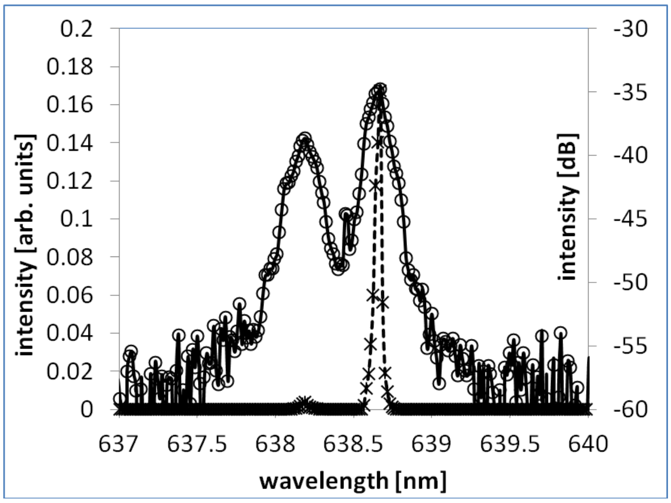


Figure 1. Spectral characteristics of the monomode laser diode measured at different resolutions. The spectrum is measured with an optical spectrum analyser in linear and logarithmic scale. The logarithmic scale (right side) reveals that there are two peaks of different intensity and that the laser is not strictly monomode (only one peak is allowed).

The laser diode has a very small active zone which leads to diffraction. Because the active zone is not symmetric the emission profile is elliptical.

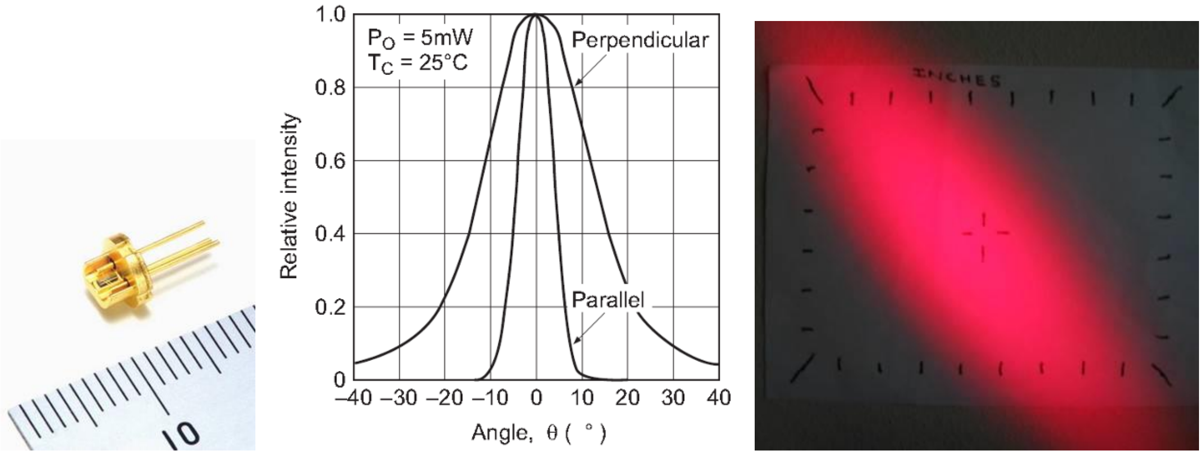


Figure 2. Appearance and emission profile of the laser diode. The emission profile is not symmetric and leads to an elliptical shape in the far field.

Halogen lamp

The halogen lamp is from International light. It is a gas filled Argon clear-end lamp driven at a design voltage of 3.5V. It drives a current of 450mA for a light output of 4.5 Lumen and a colour temperature of 2270K. The lamp has a lifetime of 30,000 hours. The filament measures 1.2 x 0.43 mm^2. It is a particular small halogen lamp. The lamp has a lens incorporated into the glass body to shape the light and pre-focus to smaller solid angles. One recognizes the large spectral width of this source.

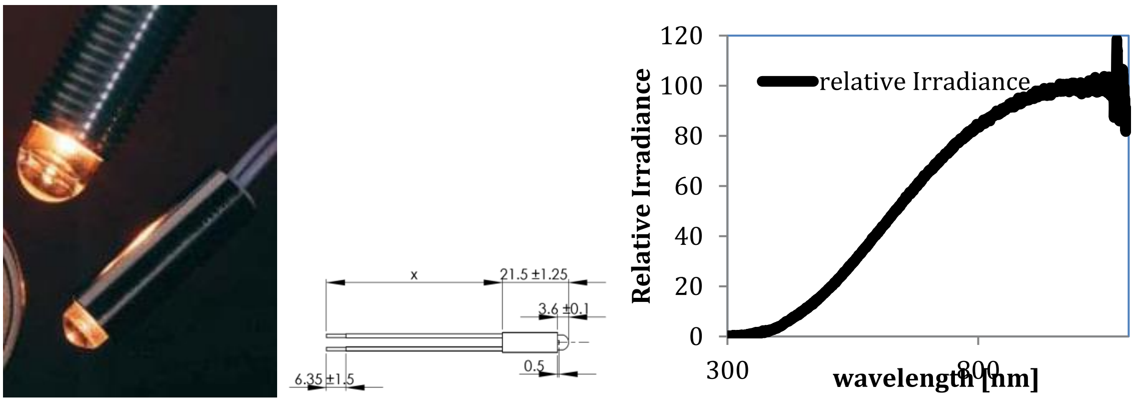


Figure 3. Appearance, dimensions and spectra of the miniaturized halogen lamp from International light. The irradiance curve could be compared to the black body emitter.

Light emitting diode

The light emitting diode LED is a solid-state light source. The peak wavelengths indicated by the supplier is 624 nm at and the spectral bandwidth at FWHM is 30 nm (Full width at half maximum FWHM). The LED is from Everlight (https://www.everlight.com), part number 27-21/R6C-AP1Q2B/3C.

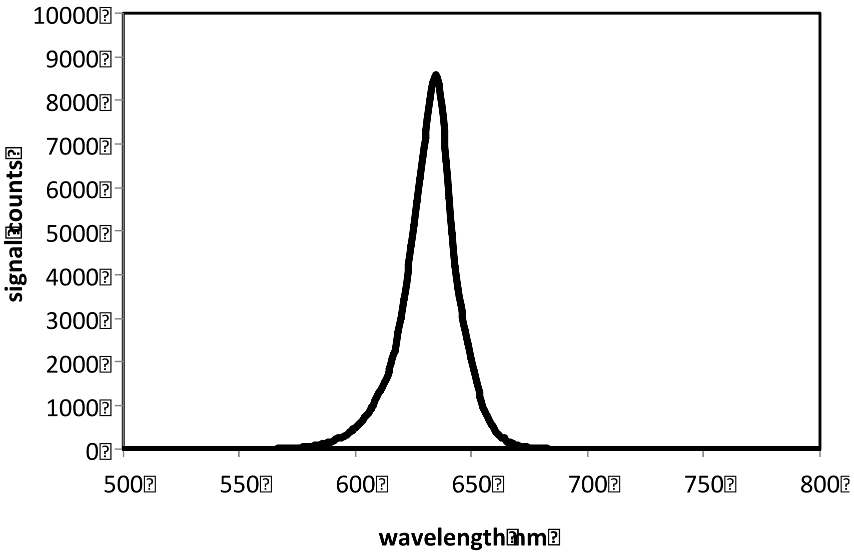


Figure 4 Spectral behavior of the red LED used in the experiments as provided by the supplier.

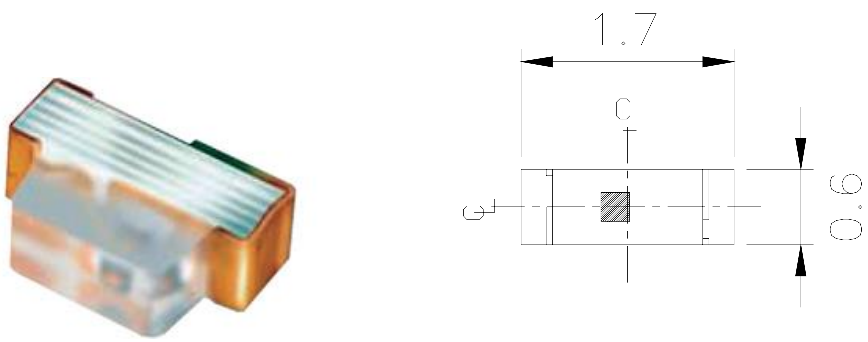


Figure 5. Appearance of the LED, its dimensions, a schematic of its construction as given by the manufacturer.

Most LEDs emit light along a preferred direction. For the current LED, the viewing angle (2 x θ) is given by the manufacturer as 130°!

Diffraction grating

The principal component of a grating spectrometer is the diffraction grating. Diffraction is an interference phenomenon that becomes important if structures size interacting with light waves become comparable to the wavelength of light. For visible light (wavelength 380-780 nm) diffraction becomes omnipresent when structures are smaller than 30 microns. Diffraction is characterized by a diffraction angle Θ which depends on the wavelength. It leads to dispersion. A grating spectrometer belongs to the class of dispersion spectrometers.

We consider a grating with period Λ illuminated with normal incidence by a plane wave of wavelength λ. At the exit of the grating one find a series of beams propagating in different directions symmetrically grouped around the initial beam. The diffracted beams have different intensities that depend on factors such as the gratings shape and the illumination conditions. An example image showing two diffraction orders and the non-diffracted zeroth order is shown below.

Figure 6. Grating diffraction for monochromatic light (red laser). Several spots appear that could be identified as the zeroth, first and second diffraction order. The intensity of all these spots is different.

The angular deviation (from normal incidence) can be described by

$$\sin\Theta = m\frac{\lambda}{\Lambda} \qquad \text{Eq. 1}$$

with the angle of deflection Θ and the so-called order of diffraction m. The angle of deflection is smaller or equal to 90°, limiting the number of diffraction order. To give an example, a grating with Λ=2 micron period illuminated with a wavelength of λ=0.5 µm (green) diffracts the light up to the third order (positive and negative). The angles are

$$\Theta_0 = 0,$$
$$\Theta_{+1} = \arcsin(0.25) = 14.4°,\ \Theta_{+2} = \arcsin(0.5) = 30°,\ \Theta_{+3} = \arcsin(0.75) = 48.6°,$$
$$\Theta_{-1} = \arcsin(-0.25) = -14.4°,\ \Theta_{-2} = \arcsin(-0.5) = -30°,\ \Theta_{-3} = \arcsin(-0.75) = -48.6°$$

Larger values of m would lead to angles larger than 90° which is not possible. Note that the **angles are not added** for different orders because of the nonlinearity of the sin function. For a grating of 20 micron period, we would find plus minus 9 order with the smallest diffraction angle of Θ_{+1}= arcsin(0.025)= 1.44°. It is clear that for larger structures the diffraction angle become so small that in realistic system with typical optical path length below 1 m the separation of orders in the system becomes small and cannot be observed anymore. Therefore, in macroscopic optical systems diffraction is often neglected.

If one wants to explore the dispersion properties of diffraction one uses a diffraction grating. Diffraction gratings can be produced by different technics. The classical ways are ruling (mechanical machining) and holography. The image below shows an example of a surface relief grating that was produced by laser beam interference (holography with two beams) and has a period of less than 2 microns.

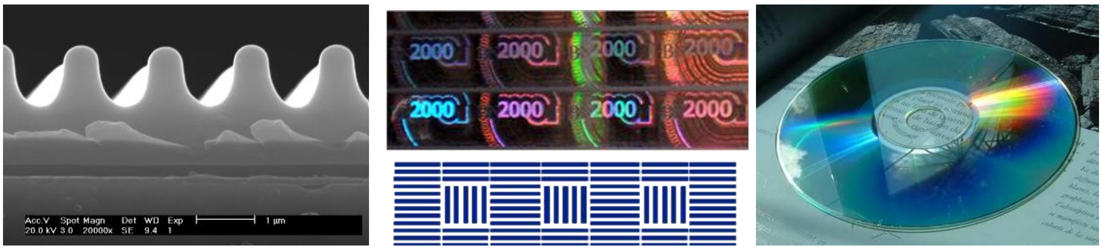


Figure 6: Left: Surface relief grating and a typical application as a security element of banknotes (middle). The schematics shows that gratings of different orientation are used to create contrast in the image. Right. Diffraction effects of a CD lead to colours. (Images: 3dAG, Web)

Oblique incidence

In real systems, the beam is often folded to save space and reflection is used. Furthermore, the grating is not used in normal incidence. A typical arrangement indicating all angles is shown below.

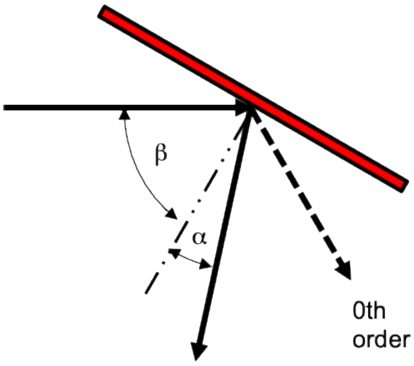


Figure 6: A grating used in reflection. Light is coming from left and impinges with an angle β onto the grating. The angle β is measured towards the normal of the grating. The specular (direct) reflection, the zero order and the deflection angle α is indicated.

In such a case, the incident angle has to be considered and the diffraction formula reads

$$\boxed{\sin\alpha + \sin\beta = m\frac{\lambda}{\Lambda}} \qquad \text{Eq. 2}$$

Note that the sign has to be considered to and one has to be very carefully in applying this formula especially when discussing the sign of the diffraction order.
As an example, we consider the case of a 2-micron grating with an incident angle of 60°. The formula reads

$$\sin\alpha = m\frac{\lambda}{\Lambda} - \sin\beta = m\frac{\lambda}{\Lambda} - \frac{\sqrt{3}}{2} \qquad \text{Eq. 3}$$

(grating period Λ, grating orders m, angle of deflection Θ). At 500 nm wavelength we find the following orders measured from the normal of the grating:

Θ_0= -60°,
Θ_{+1}= arcsin(0.25-0.866)=-38.0°,

Θ_{+2}= arcsin(0.5-0.866)=-21.5°,
Θ_{+3}= arcsin(0.75-0.866)=-6.66°,
Θ_{+4}= arcsin(1-0.866)=-6.66°,
Θ_{+5}= arcsin(1.25-0.866)=22.6°,
Θ_{+6}= arcsin(1.5-0.866)=39.3°,
Θ_{+7}= arcsin(1.75-0.866)=62.1°,

There is no negative order because that would lead to arcsin(>1) which is not defined but there are orders with positive angles. The overall number of orders has increased from 7 for the transmission case to 8 for the reflection case (counting positive and negative orders separately)

Grating dispersion and resolution

The spectrometer uses the dispersion of the grating, that is its ability of creating different deflection angles for different wavelengths. The figure below gives an idea on what happens. Shorter wavelengths are less deviated than longer ones for one and the same grating.

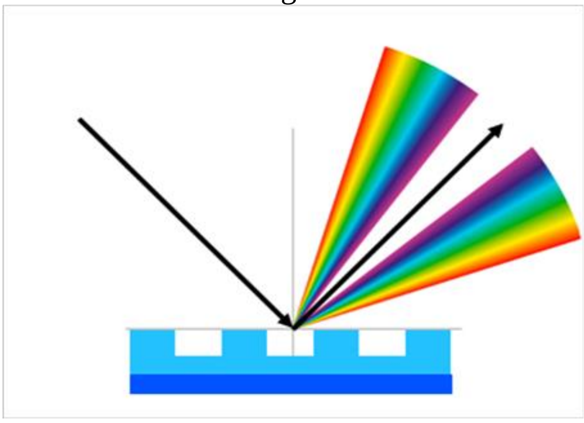


Figure 8: Gratings create different reflection angles for different wavelengths and lead to an angular separation. This dispersion is used to project the light on different positions for analysis.

The power of dispersion can be calculated with the grating formula. We are looking for the change of angle α as a function of the wavelength λ. Partial derivation of Eq. 2 (β is a constant) gives the dispersion:

$$\frac{d\alpha}{d\lambda} = \frac{m}{\Lambda}\frac{1}{\cos\alpha} \qquad \text{Eq. 3}$$

We see that the dispersion is larger for higher orders m and for smaller grating periods Λ.
The resolution (the capability of discrimination between two wavelengths) is limited by the finite beam size and its divergence. A beam with a diameter D will show a divergence angle $\theta=\lambda/D$. The effect can be understood by analogy with a slit of width D, the size of our beam. Diffraction at the slit leads to an angular spread with a typical angle $\theta=\lambda/D$. In our problem, the change of the deviation angle $\Delta\alpha$ should be larger than the diffraction angle θ hence $\Delta\alpha > \theta$. Therefore,

$$\Delta\alpha = \frac{m}{\Lambda}\frac{1}{\cos\alpha}\Delta\lambda > \frac{\lambda}{D} = \theta \qquad \text{Eq. 4}$$

and by rewriting we get:

$$\frac{\Delta\lambda}{\lambda} > \frac{\Lambda}{D}\frac{\cos\alpha}{m} \qquad \text{Eq. 5}$$

The term D/Λ is the number of illuminated grating lines. To obtain a fine resolution, a large number of grating lines have to be illuminated. Increasing m has the same effect. To be more specific; if one uses a Λ=2 micron grating at λ=500 nm in the first order with a beam size of D=10 mm and at β=30° incident angle the theoretical grating resolution Δλ/λ is approximately 0.0002, which is at 500 nm Δλ=0.1 nm. In this case one illuminates 5000 lines! **Note, the larger the illuminated grating area (beam diameter D) is the better is the resolution.**

Spectrometer operational principle

Beside the theoretical **grating resolution** there is also an **instrument resolution**. This is linked to the design of the spectrometer that contains slits and lenses as well as a detector with a certain number of pixels.
In a real system, a possible configuration is shown below.

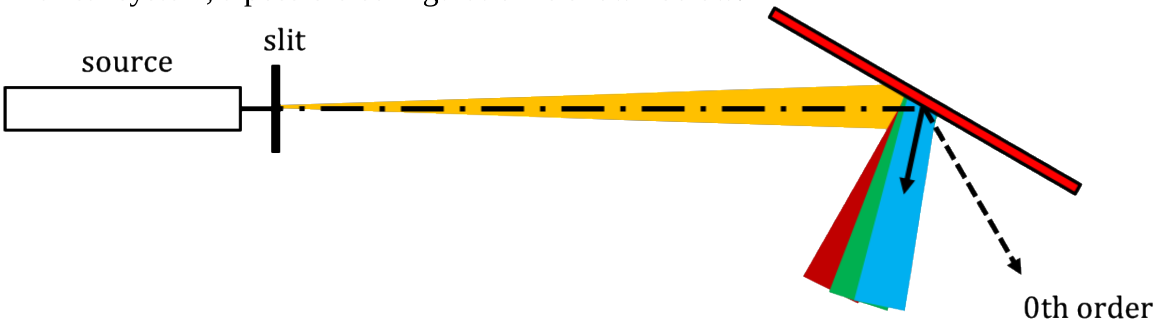


Figure 9: The light is diffracted by the grating and sent back into different directions depending on grating diffraction orders and wavelengths.

The light is diverging and should be refocused. Usually mirrors or lenses are used. Mirrors have the advantage of being achromatic. We will use a lens as in the configuration sketched below.

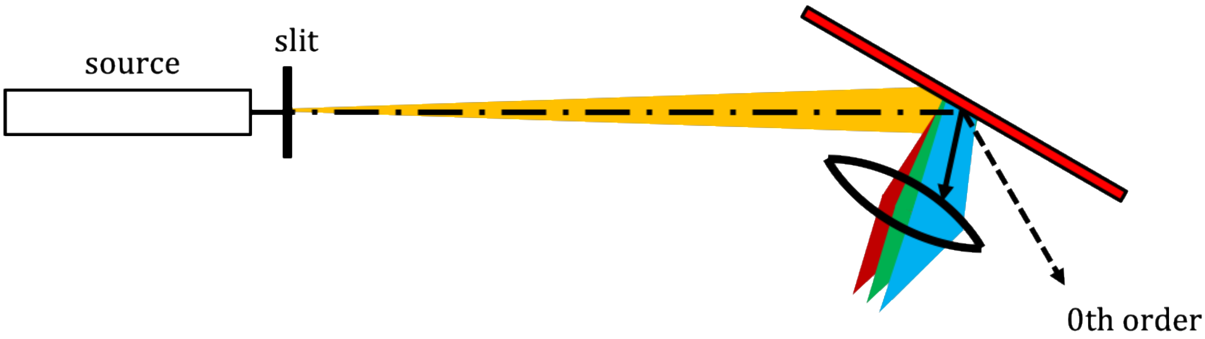


Figure 10: The lens focuses the grating orders on the imaging plane.

If a lens is used after the grating the diffracted light can be focussed on the detector. To get a high resolution, the **image of each diffraction order should be small**; hence the object should also be small. Usually, a slit is used. In this case, the slit is imaged on the detector. When the slit is located far away from the grating, the light is nearly parallel. The grating redirects the light for each order and wavelength in a different direction. The grating has certain dispersion, i.e., it distributes the wavelengths over a well-defined angular range for each order. The shorter the grating period the larger is the dispersion. In our case we use a compact disc (CD) with a period Λ=1.6 micron. **The lens collects the light within a certain angular range and makes an image of the slit onto the detector**. We can use simple arrows to represent the image for each wavelength in a situation when the slit is assumed to be at infinity (It is at 110 mm compared to the focal length of the objective that is f=3.7 mm). The image above shows the situation for the first order diffraction. It is possible that several orders can be captured by the system if the angular field of view of the camera is large enough. Then one observes several orders as sketched below.

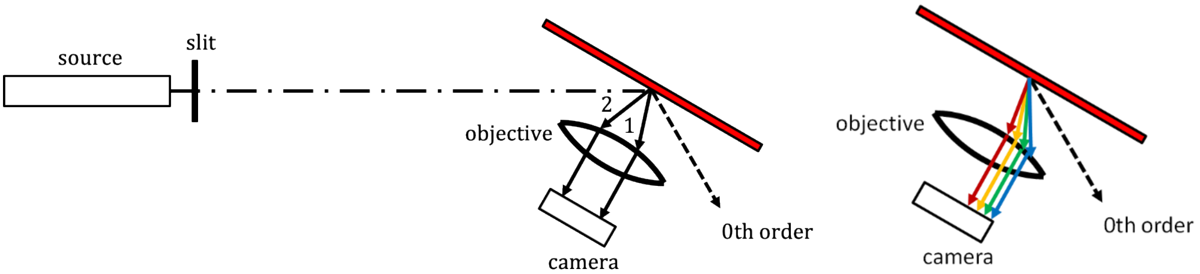


Figure 11. If the field of view is large several diffraction orders appear on the camera.

For white light illumination, a typical image is shown in the figure below.

Figure 12: First and second diffraction orders for a white light source.

Resolution

Let us now consider the resolution of our spectrometer. **The objective creates an image of the slit on the detector at different positions for different wavelengths**. To clarify the dependence, we have sketched the geometry below.

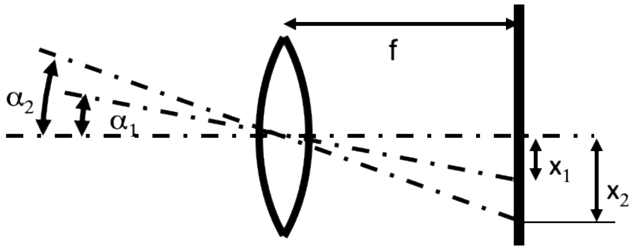


Figure 13: Projection of rays coming from different directions from infinity onto the detector. The rays reach the detector at different angles.

We want to calculate the dispersion, the position as a function of the wavelength, on the detector. Each angle gives a different position on the detector and the link is given by the focal length (because we are coming from infinity).

Position and angle are related by simple equations such as

$$x_i = f \tan \alpha_i \qquad \text{Eq. 6}$$

For small angles we can simplify the equation by linearization

$$x_i = f\alpha_i \qquad \text{Eq. 7}$$

Now we consider the dispersion in space that is the change of position against the wavelength $\Delta x/\Delta\lambda$ and we substitute the value for Δx by using Eq. 7 and the angular dispersion of the grating with Eq. 3.

$$\frac{\Delta x}{\Delta\lambda} = f\,\frac{d\alpha}{d\lambda} = f\,\frac{m}{\Lambda}\frac{1}{\cos\alpha} \qquad \text{Eq.8}$$

Our detector has a pixel pitch of 2.835 micron and that is the minimum spatial resolution Δx we can safely achieve, hence Δx=2.835 micron. The corresponding $\Delta\lambda$ is calculated as

$$\boxed{\Delta\lambda = \frac{\Lambda}{f}\frac{\cos\alpha}{m}\Delta x \approx \frac{1600\text{ nm}}{3600\ \mu\text{m}}\frac{1}{1}2.85\mu\text{m} = 1.26\text{ nm / pxl}}$$

In this calculation we used a grating pitch of Λ=1600 nm, the focal length of f=3.7 mm, the first order (m=1) and we set cos α equal to one. This value is about 10 times larger than the theoretical grating resolution calculated above which was approximately 0.1 nm for a grating illuminated with a 10 mm spot.

Optimal condition

Under optimal conditions, the image of the slit is smaller than the pixel size. To realize this, we have to consider the imaging of the slit by the objective and the corresponding magnification. Using the object distance d_O and the image distance d_I the magnification m is expressed as

$$m = \frac{d_I}{d_O} \qquad \text{Eq. 9}$$

This value corresponds to the ratio of the slit width w (in object space) and the slit width (in image space). the latter should not exceed the pixel size Δx. We find

$$m = \frac{d_I}{d_O} = \frac{\Delta x}{w} \qquad \text{Eq. 10}$$

We want to calculate the optimal object (slit) distance. We have

$$\frac{1}{f}=\frac{1}{d_O}+\frac{1}{d_I}=\frac{1}{d_O}+\frac{1}{m\,d_O}=\frac{1}{d_O}\left(1+\frac{1}{m}\right) \qquad \text{Eq 11}$$

This relation can also be expressed in as

$$\frac{1}{f}=\frac{1}{d_O}+\frac{1}{d_I}=\frac{m}{d_I}+\frac{1}{d_I}=\frac{1}{d_I}(m+1) \qquad \text{Eq. 12}$$

If the magnification m is small d_I is almost equal to f and one finds

$$m=\frac{d_I}{d_O}\approx\frac{f}{d_O}=\frac{\Delta x}{w} \qquad \text{Eq. 12}$$

Let us consider the following parameters:

- slit width w = 100 micron
- pixel size Δx = 2.85 micron
- focal length f = 3.6 mm

The desired magnification is m=2.85/100 (pixel/slit width) and using Eq. 11 to calculate d_O

$$\boxed{d_O=f\left(1+\frac{1}{m}\right)=3.6\left(1+\frac{100\ \mu\text{m}}{2.85\ \mu\text{m}}\right)\text{mm}=130\ \text{mm}}$$

Furthermore, we can state that the approximation d_O>>f is valid.

Spectral measurements

To perform spectral measurement the grating spectrometer has to be calibrated. There are two calibrations to be done:

- Calibration in wavelengths
- Calibration in intensity

Each wavelength is imaged (via the slit image) onto a specific position onto the detector. The positions are defined by the grating formula and the imaging conditions. Too many parameters are involved because all curves are nonlinear. Usually, the calibration is done by using a calibration lamp with known and sharp spectral lines (discharge lamp). It can also be done with colour glass or interference filters of known spectral characteristics. We use filters with defined cut of wavelength.

To compare signals of different spectral intensity an **intensity calibration** is needed because the detector, the grating and lamp (if transmission has to be determined) have a not very well specified and reproducible characteristic. Calibration lamps based on black body radiation are used for calibration and could give a relative (or absolute) irradiance value per wavelengths. Intensity calibration will not be further considered here. Please refer to the specialized literature for details.

Limiting factors

Grating spectrometers have the advantage of measuring in parallel. But there are also certain disadvantages.

Spectral overlap

The grating has more than one diffraction order and for a large spectral range the longest wavelength of the first order might overlap with the shortest wavelength of the second order. An example for the second order overlap of a 2.5 micron grating in normal incidence is shown below.

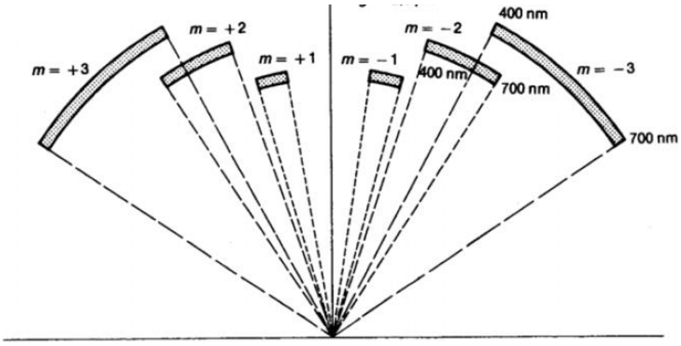


Figure 14 Spectral overlap that appears for grating orders and large spectral ranges.

The overlap of different orders can be managed by using special filter technology.

Grating efficiency and detector efficiency

Both the detector and gratings have particular spectral characteristics, which have to be optimized for large spectral ranges measurements.

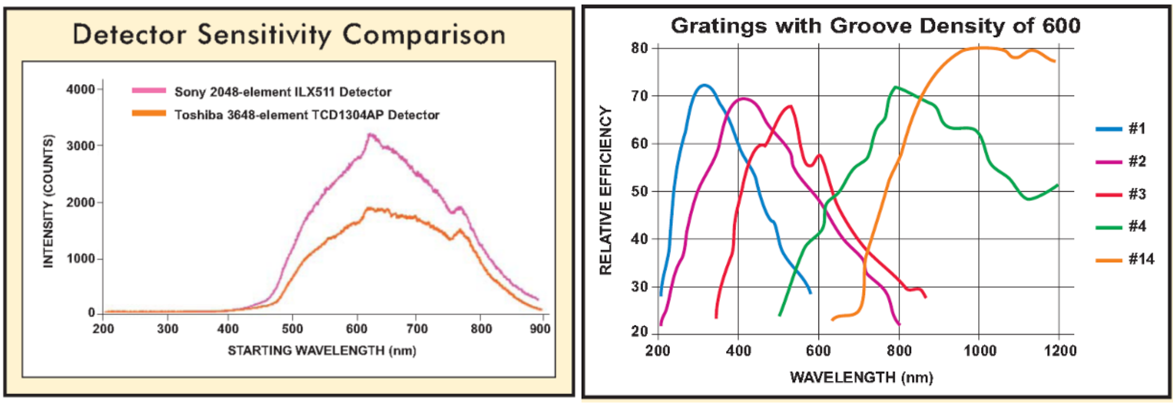


Figure 15: Sensitivity curves for different silicon detectors (left) and some grating efficiency examples (right). Source: The Ocean optics catalogue

Stray light

When light is scattered inside the spectrometer it can hit the detector at places that where it should not. This creates noise onto the detector and the signal to noise ratio is decreased. Stray light is often the limiting factor.

Examples

For focussing the objective can be replaced by a concave mirror that incorporates a grating to come to a very elegant solution. Examples are shown below.

1 SMA 905 Connector
Light from a fiber enters the optical bench through the SMA 905 Connector. The SMA 905 bulkhead provides a precise locus for the end of the optical fiber, fixed slit, absorbance filter and fiber clad mode aperture.

2 Fixed Entrance Slit: specify slit size
Light passes through the installed slit, which acts as the entrance aperture. Slits come in various widths from 5 µm to 200 µm. The slit is fixed in the SMA 905 bulkhead to sit against the end of a fiber.

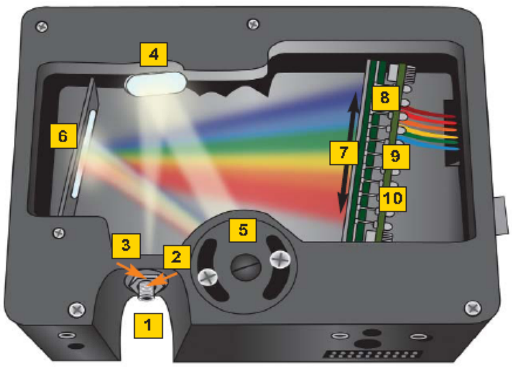
3 Longpass Absorbing Filter: optional
If selected, an absorbance filter is installed between the slit and the clad mode aperture in the SMA 905 bulkhead. The filter is used to block second- and third-order effects or to balance color.

4 Collimating Mirror: specify standard or SAG+
The collimating mirror is matched to the 0.22 numerical aperture of our optical fiber. Light reflects from this mirror, as a collimated beam, toward the grating. You can opt to install a standard mirror or a UV absorbing SAG+ mirror.

5 Grating & Wavelength Range: specify grating & starting wavelength
We install the grating on a platform that we then rotate to select the starting wavelength you've specified. Then we permanently fix the grating in place to eliminate mechanical shifts or drift.

6 Focusing Mirror: specify standard or SAG+
This mirror focuses first-order spectra on the detector plane. Both the collimating and focusing mirrors are made in-house to guarantee the highest reflectance and the lowest stray light possible. You can opt to install a standard or SAG+ mirror.

7 L4 Detector Collection Lens: optional
This cylindrical lens, made in-house to ensure aberration-free performance, is fixed to the detector to focus the light from the tall slit onto the shorter detector elements. It increases light-collection efficiency.



8 Detector
We offer a 3648-element Toshiba TCD1304AP linear CCD array detector. Each pixel responds to the wavelength of light that strikes it. Electronics bring the complete spectrum to the software.

9 OFLV Variable Longpass Order-sorting Filter: optional
Our proprietary filters precisely block second- and third-order light from reaching specific detector elements.

10 UV4 Detector Upgrade: optional
When selected, the detector's standard BK7 window is replaced with a quartz window to enhance the performance of the spectrometer for applications <340 nm.

Figure 16. Details from the Ocean optics catalogue that shows the components of a miniaturized compact spectrometer.

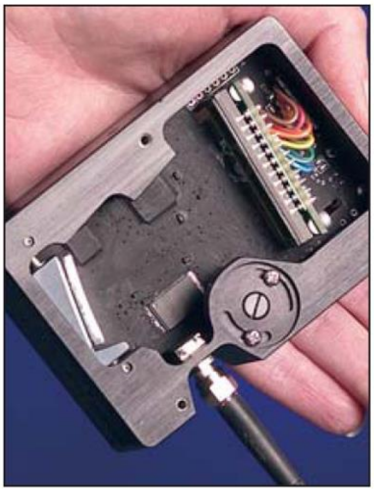


Figure 17: Realization of the instrument above (Ocean optics catalogue)

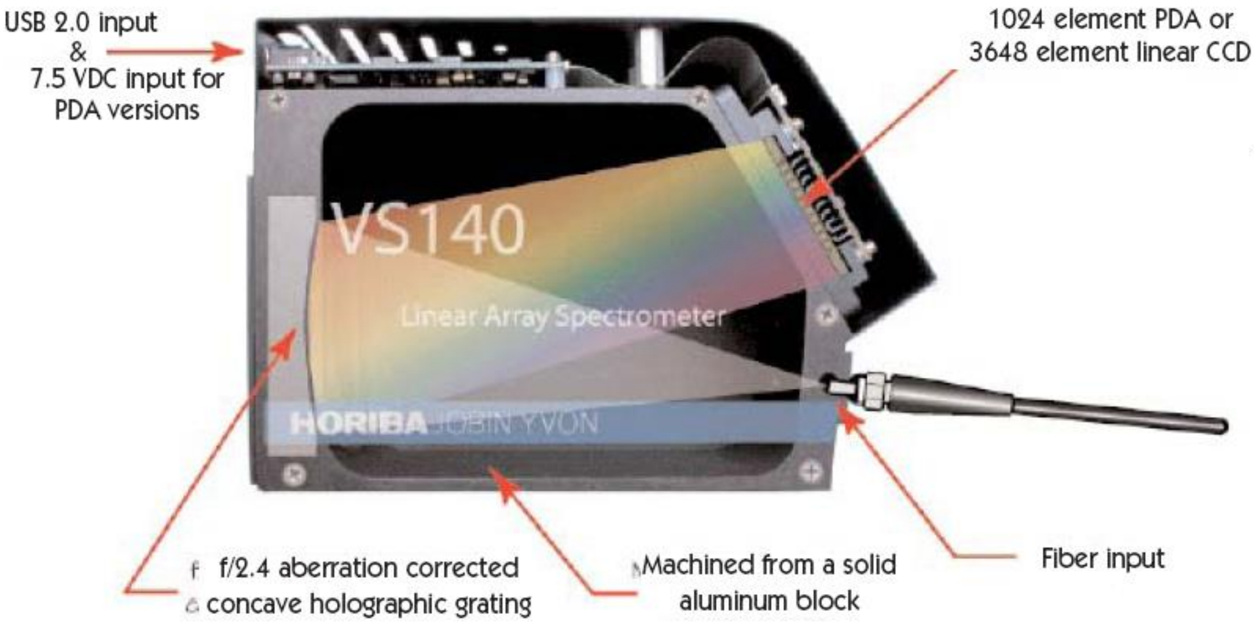


Figure 18. Horiba Yvon miniature spectrometer with concave mirror grating and fibre input.

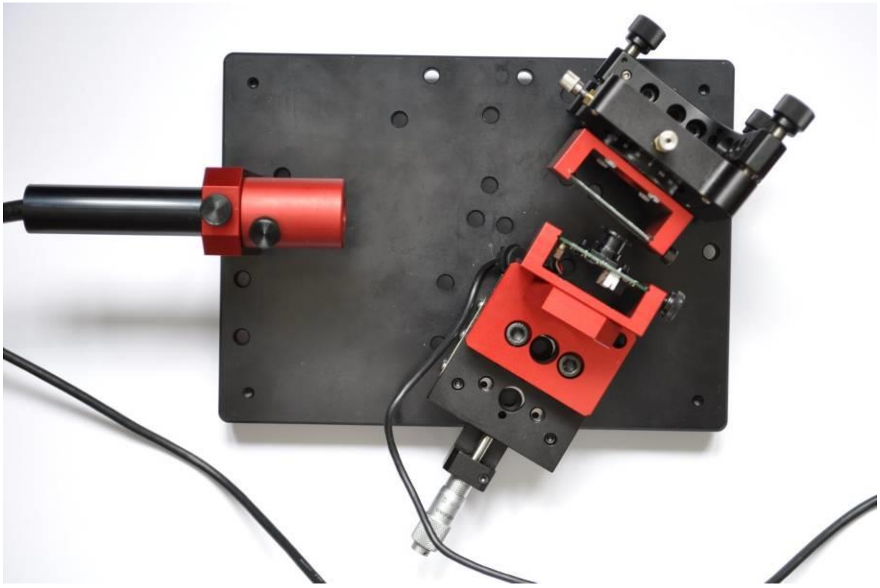
3 Setup and equipment - tasks of the experimental work

3.1 Setup and adjustment

Materials

- CMOS USB camera
- CD-ROM grating (1.6-micron pitch)
- Laser diode, USB driven
- Halogen source
- LED source
- Filter set (coloured glass plates)

Mechanical holders and setup



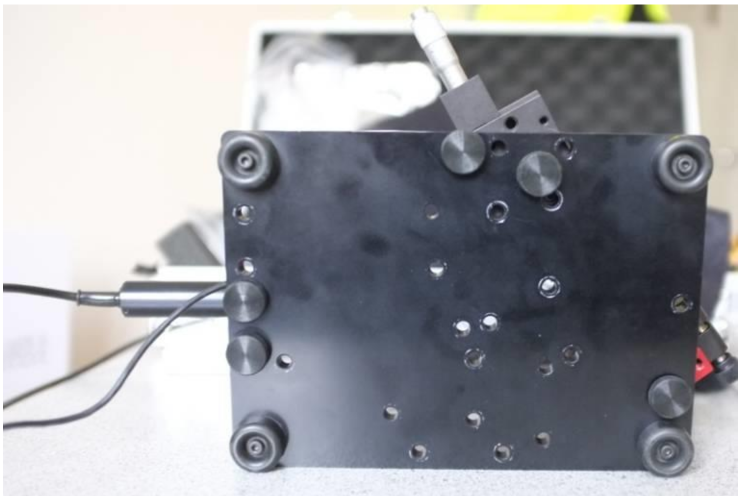


Figure 19: Top view of the grating spectrometer and position of the fixing screws as seen when tilted along the long edge of the breadboard. The source is still on the left side.

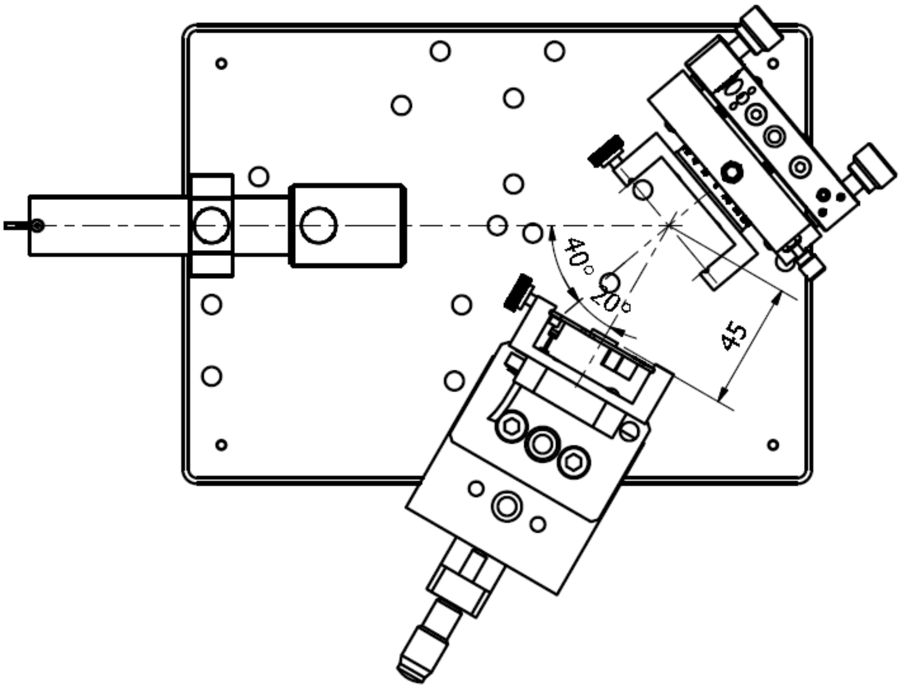


Figure 20: Schematic view of the mechanical setup in top view. The exact position of the 6-axis stage has to be chosen carefully to optimize the camera's field of view and the orders to be detected. Please note that the linear stage is put much closer for suppression of the zero order.

Detached pieces

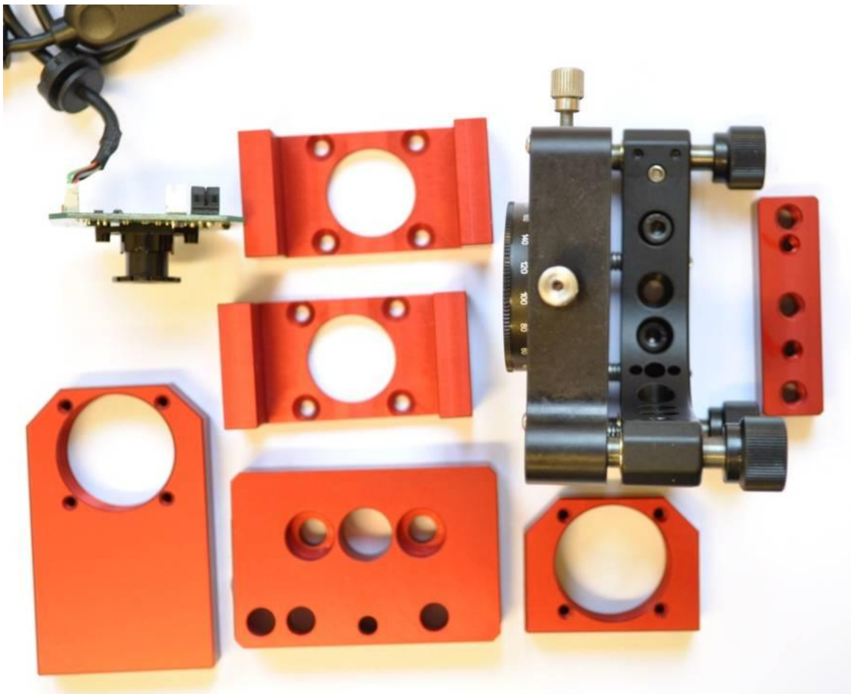


Figure 21. Mechanics needed for the setup.

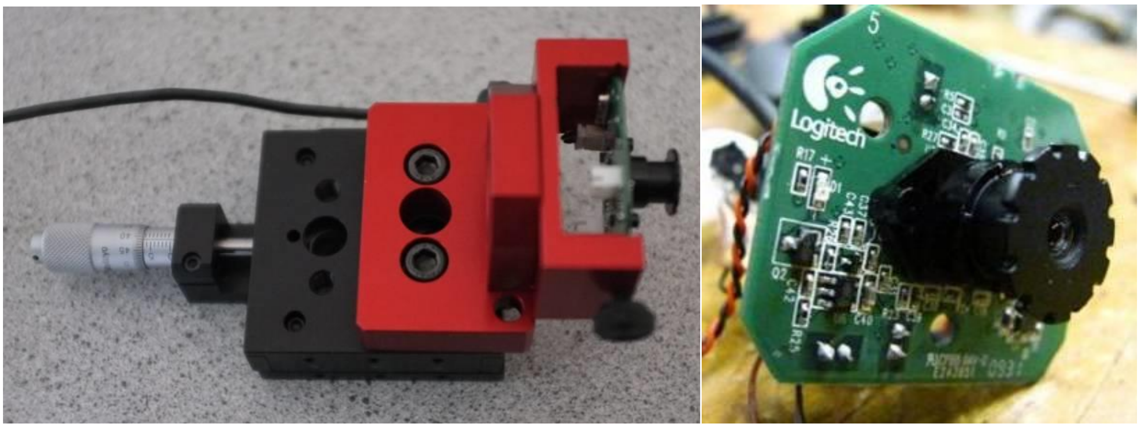


Figure 22. The camera is mounted on the translation stage WITH the objective. It could be mounted on different positions on the translation stage (compare to Figure 1.)

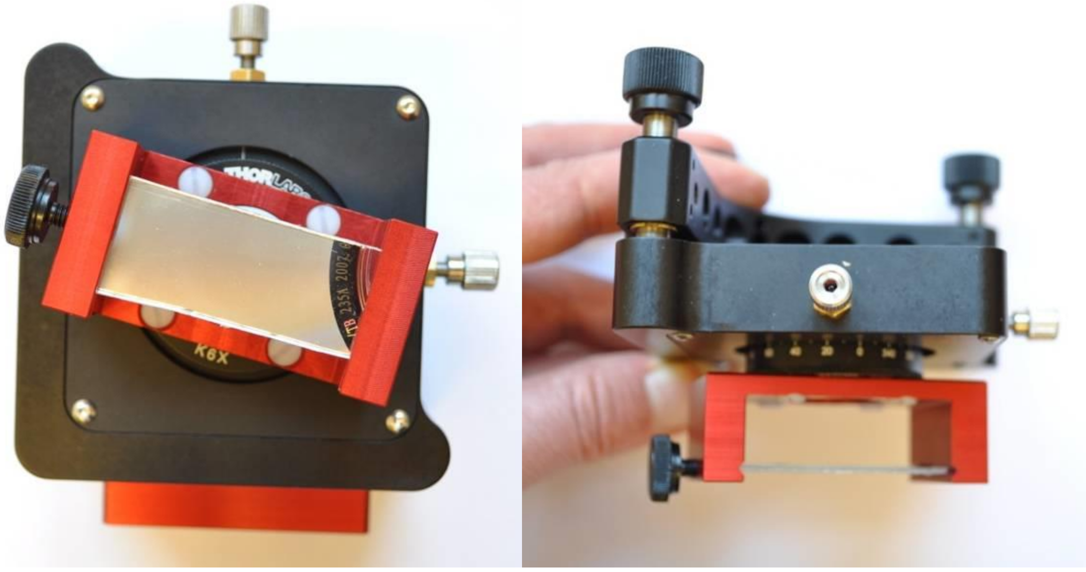


Figure 23. As a grating we use a part of a CD rom (pitch 1.6 micron). An additional camera holder is used to fix it. NOTE, that you have to use the **PLASTIC SCREWS** to mount the holder on the 6-axis stage.

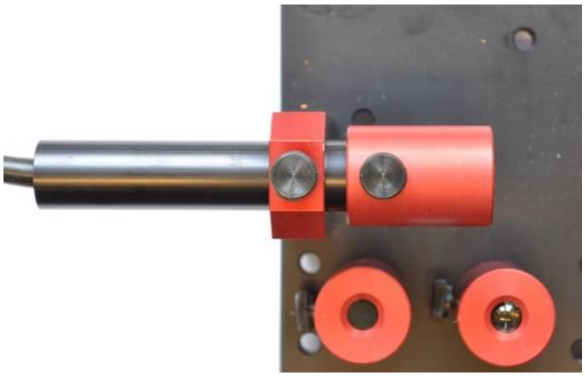


Figure 24. Several sources will be used. A laser for alignment and two sources for measurements. The slit and the lens are detached to a red cap that can be fixed on the source directly.

Spectrometer setup and alignment

- Mount the spectrometer as shown
- The 6-axis stage is fixed with only ONE screw to allow rotation.
- Use the laser source without any cap
- Switch on the camera (automatic exposure.)
- Find and image of the diffraction orders with your camera by ROTATING the 6-axis stage and grating.

You should see images like below:

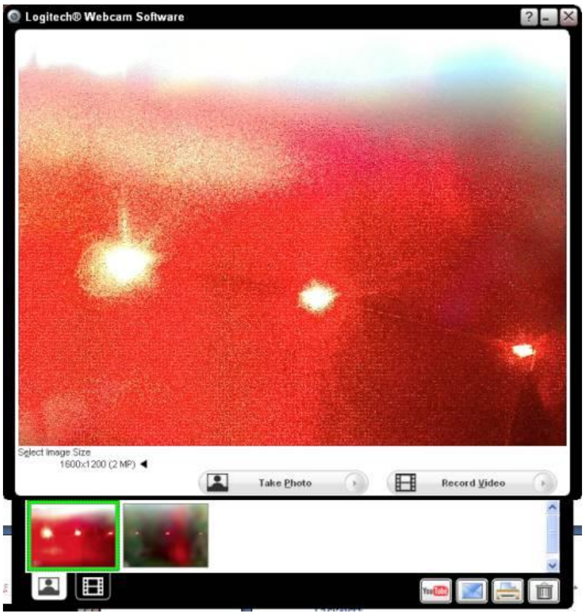


Figure 25. Diffraction effects created by the laser showing different orders of diffraction.

With this, the system is aligned and by rotating the 6-axis stage and the grating you can change the position of the diffraction orders on the camera and their orientation. The zero order has very high intensity and is easily identified.

Spectrometer adjustment

To make measurement the spectrometer needs to be further adjusted. The next step is to focus the slit with the camera objective.

- Mount the laser
- Mount the slit (red cap) on the source (laser).
- Turn the slit to be vertically oriented.

It is important to define a fixed position with respect to the grating geometry. Set the red cap such that IT TOUCHES the source holder (as shown in the figure below).

EPFL

Figure 26. If the slit cap is put in contact with the source holder a good definition of the slit position is achieved. This is important because the sources will be exchanged!

- Turn the 6-axis stage to get the slit into the field of view. It might be necessary to change the position of 6 axis stage or linear translation stage. Adjust the position to get the two diffraction orders in the field of view. After exposure adjustment, the image should be similar to that shown in the following figure.

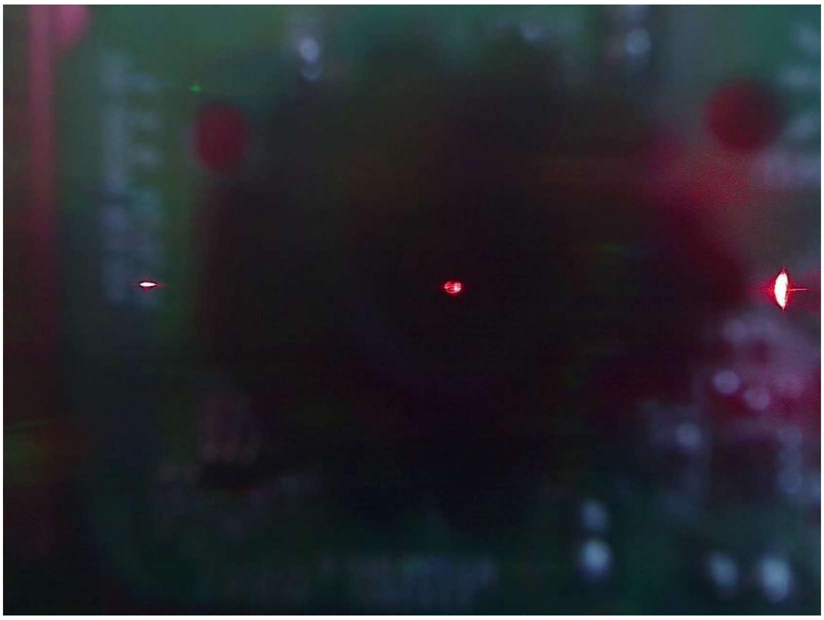


Figure 27. The three-diffraction order 1, 2,3 produced by the laser. This image helps to align the orders horizontally and define the order number.

Next you have to focus the slit

- Turn the objective of the camera to bring the slit into focus. Be careful not to misalign your spectrometer. There is only a limited space between the objective and the grating.
- The image you should obtain is similar to Fig. 28

Figure 28. Same as Fig. 27 but with the slit in focus. On the very right the magnified image of the slit is given to show the focalisation.

Now it is time to change the source and use the halogen lamp. The corresponding images with slit and after exposure correction might look like the figure shown below.

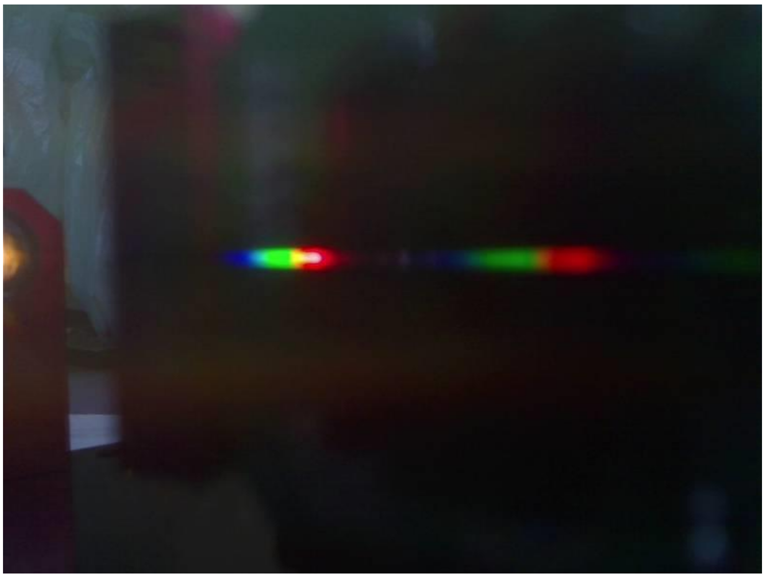


Figure 29. Adjusted the spectrometer to show two orders of diffraction. In this example the first order is on the left and second order on the right. On the very left you still see the halogen source.

To get a good contrast and signal to noise ratio stray-light should be avoided. Cover your experiment with the black tissue!

3.2 Calibration

A crucial point in spectrometer setup is the wavelengths calibration. The position of the wavelengths is not linear on the detector. One needs a wavelength position calibration. This can be done if one uses light of known wavelength (like a lamp with peaks). We will use colour filters that gave dedicated spectra.

OG515 OG 530 OG 550 OG 570 OG 590 RG610 RG 630 RG 645 BG36

Figure 30 Long pass colour filters and band pass filter (BG36) used in the experiment. There should be nine filters

The filter absorbs light below a certain wavelength, the cut-off wavelengths. The cut-off wavelength is encoded in the name i.e., OG590 transmits light above 590 nm. Each filter has a dedicated colour appearance. Put them in order of their colour appearance from yellow to red to identify the wavelength with the help of figure 30.
Introduce a filter in the optical path. This is best done in front of the source by just holding it.

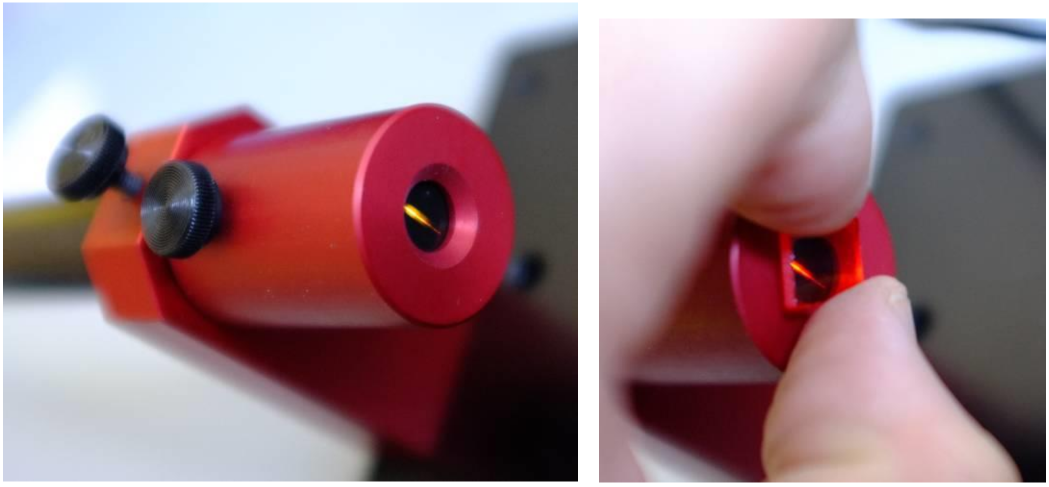


Figure 31 Application of the filter directly on the slit cap.

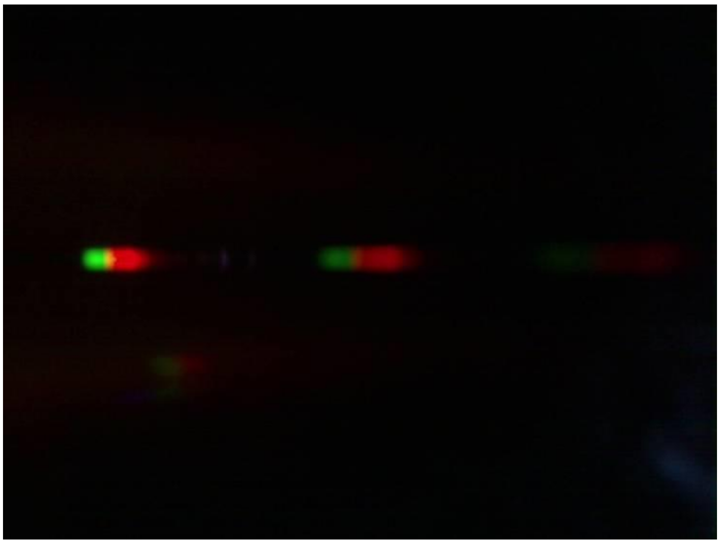


Figure 32 Spectra observed with the colour filter OG550 nm.

- Calibrate your spectrometer with several colour filters. (OG515, OG530, OG550, OG570, OG590, RG 610, RG645). Take images of each of the filter.
- Adjust the exposure condition to have enough light to identify the two diffraction orders.
- To access averaging put the spectra as horizontal as possible.

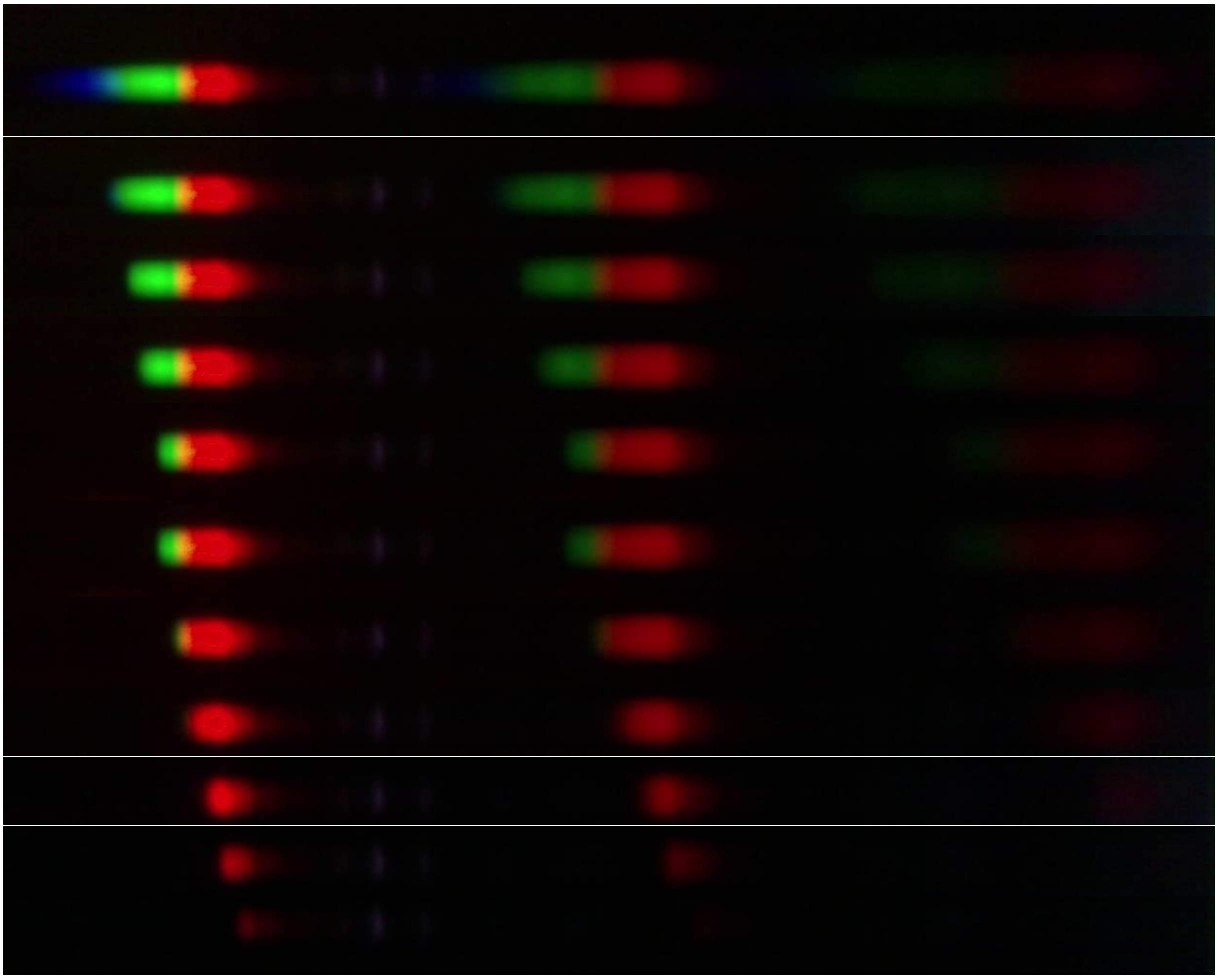


Figure 33. Images defining the position of different wavelengths with interference filters. (Top to bottom initial spectra, OG515, OG530, OG550, OG570, OG590, RG 610, RG645)

DO NOT MOVE ANY PART OF THE SPECTROMETER FROM NOW ON. BE ESPECIALLY CAREFUL THAT THE GRATING IS NOT ROTATED BY ACCIDENT!! ALL MOVEMENTS SPOIL YOUR CALIBRATION THAT HAS TO BE DONE AGAIN!

Evaluation

The wavelength scale is not linear and usually calibrated with a polynomial fit of second order.
The images have to be plotted and line plots of the intensity have to be compared. Use MATLAB to follow the evaluation procedure. You have to load images and plot their intensity profiles at the position of the diffraction orders. To evaluate the curves the positions of the diffraction spots in the images has to be found. You can do this by plotting an image and use the curser to find the line number.

- Search the pixel position that contains the information and evaluate the approximate height. In our example it is at 530 and approximately 30 pixels high (530-560).

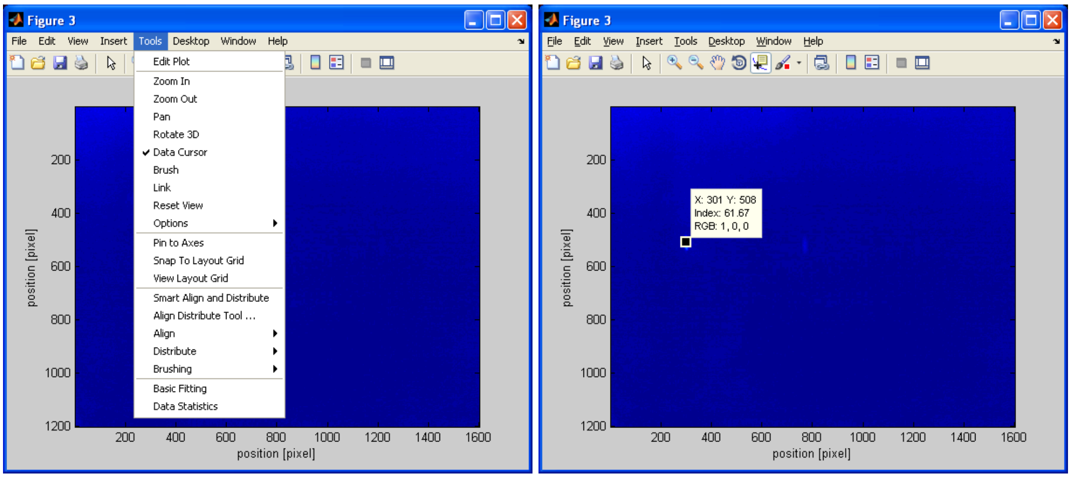


Figure 34: Data cursor can be chosen in the FIGURE under TOOLS -> Data Cursor and allows to find the positions of peaks.

- Adjust the values for pixel and averaging range (ROI)
- Find the edge positions. Use the data cursor to find the edge positions at Full width half maximum
- Make a table with edge wavelengths and position and provide a plot
- Fit a quadratic curve and find fitting parameters. (i.e., with Excel)

We used the script “Calibration_SpectraLinePlot” to plot several lines in the same image. (Code is attached in the Annex). Do not forget to correct the ROI (!!) and position of your intensity line.

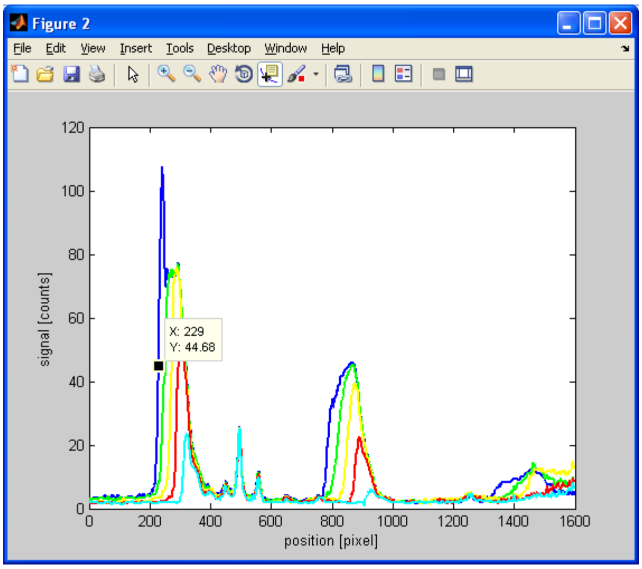
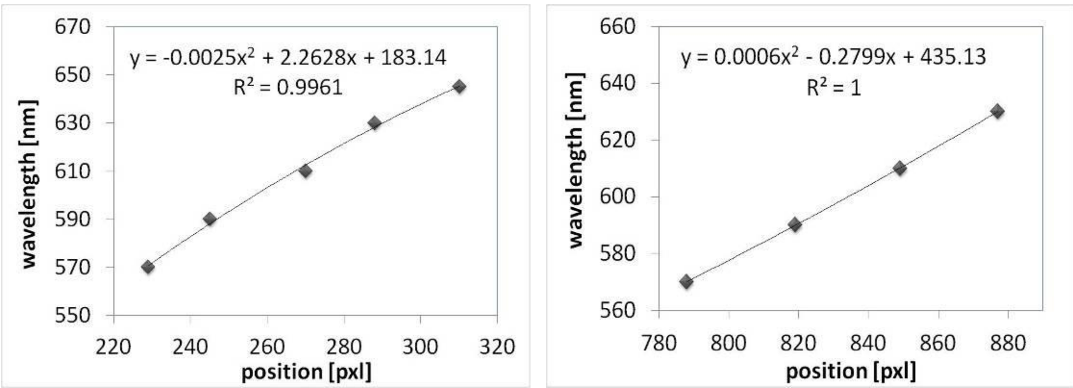


Figure 35. Intensity plots the filters at 570 and for all calibration filters up to 645 nm. The edge position can be evaluated directly in the image by using the data cursor.

In our example here, we get

Calibration wavelengths (nm)	**First order edge position (pxl)**	**Second order edge position (pxl)**
570	229	788
590	245	819
610	270	849
630	288	877
645	310	915



First order Second order

Figure 36. Example calibration curves for the first and second order and the corresponding quadratic fit functions.

To be done for the report: Show example pictures of your calibration for two different filters (i.e., 590 nm and 630 nm, two images). Measure a wavelength calibration curve with a minimum of 4 points for the first **and** the second diffraction order (for instance: 570 nm, 590 nm, 610 nm, 630 nm, 645 nm, wavelength versa position). Put it in a tabular form as shown above (table). Fit a second order polynomial and give the equation and plot the curves (two plots, calibration equations). Comment your results.

3.3 Transmission of a band pass filter

Transmission is measure by comparing an initial reference signal (white) with an actual signal. One has thus to make two measurements and divide the two signals through each other. The measurement gives the following results.

Reference signal

BG36 signal

Evaluation is done with the MATLAB script “Transmission_LinePlot.m” and gives the following curve. (Do not forget to adjust the ROI!)

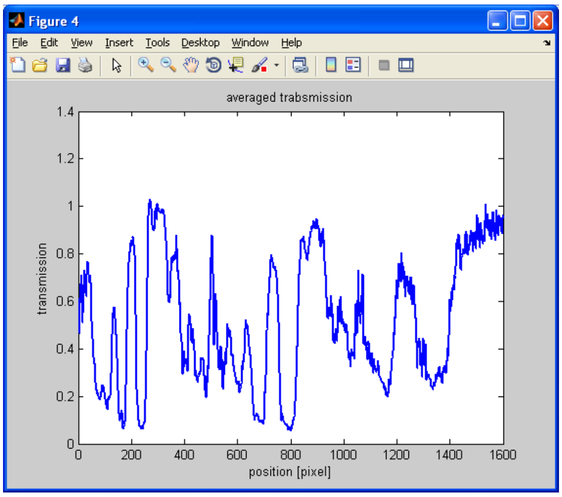


Figure 37. Transmission line plot of the filter BG36.

To be done for the report: Show the spectra and the transmission measurement for the filter BG36 (two plots). Interpret the spectra with the help of the transmission line plot. Remember that transmission has values between one and zero. Copy a plot of the transmission curve of the datasheet as given by SCHOTT (Annex) and compare with your measurement. Find similarities.

3.4 Spectral measurement of an LED

Next, we want to evaluate the spectra of the LED. You should apply the following procedure:

- Change the source and use the LED.
- Be careful to not misalign the spectrometer.
- Put the slit in front of the LED (red cap as shown above) and assure contact of the cap with the holder to have the same slit position.
- Turn the slit to be vertically oriented.
- Adjust the intensity to avoid saturation.
- Take an image.

The result should be similar to the figure below.

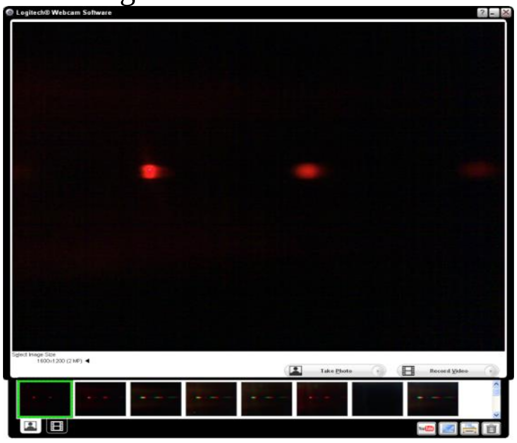


Figure 38. Spectra of an LED measured the grating spectrometer.

Evaluate the peak position of the LED.

A typical measurement is shown below. Evaluation is done with the MATLAB script “SpectraLinePlot.m”

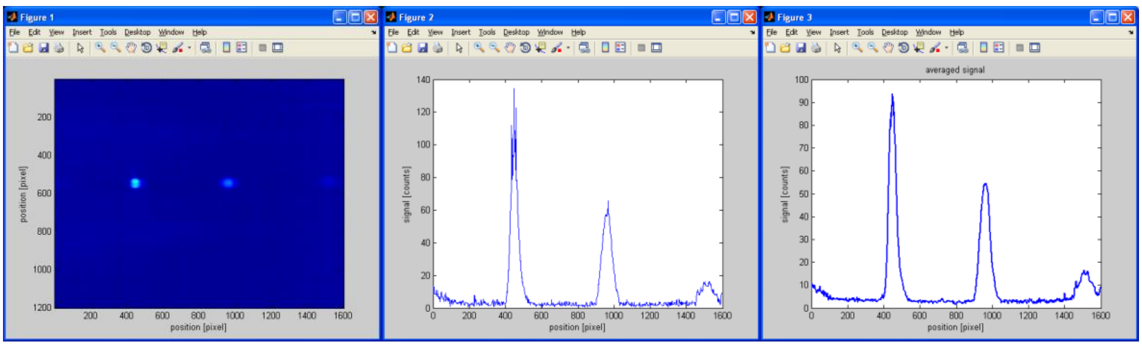
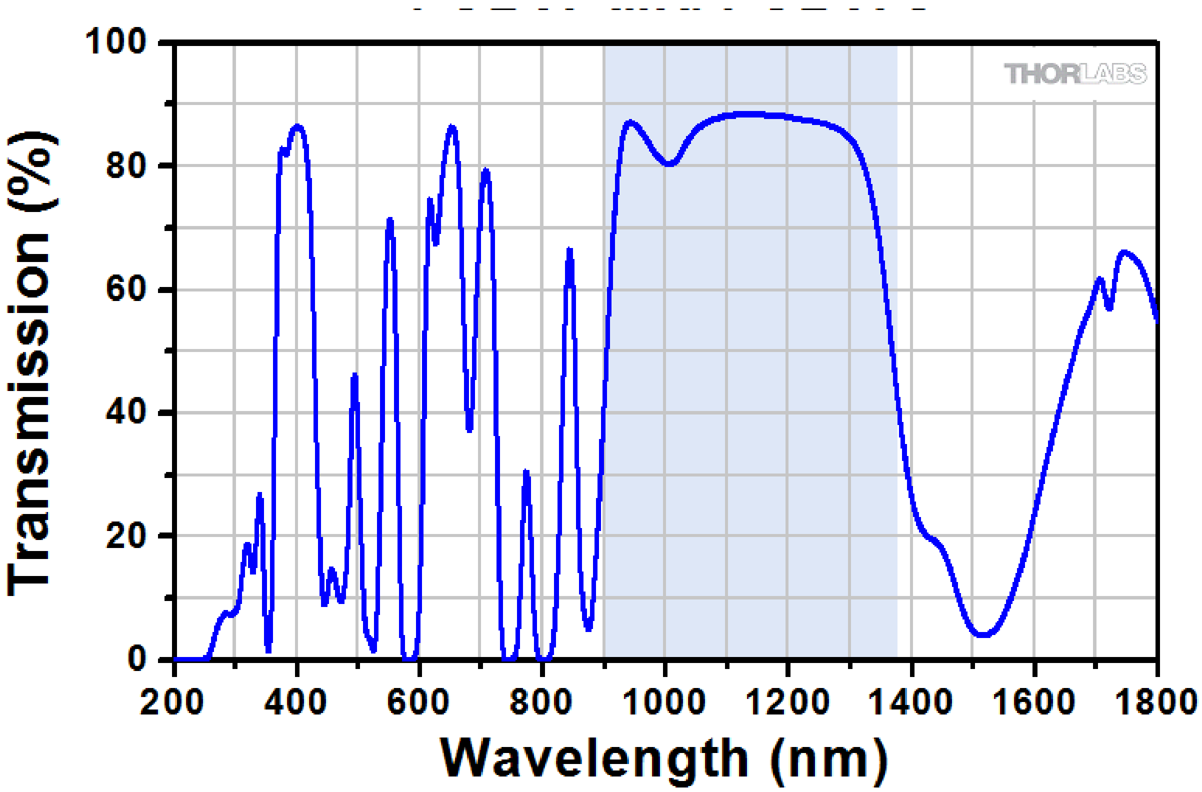


Figure 39 A complete sequence if the LED spectra measurement (first and second order) having a much larger width as the calibration spectra.

The peak position and centre wavelengths are summarized below. Linear interpolation leads to a centre wavelength.

- What is the difference if one uses the first or the second order for spectral evaluation?
- Is it advantageous to use the second order for the measurement?

Filter characteristics BG36



Filter characteristics OG and RG, **LOGARITHMIC SCALE!**