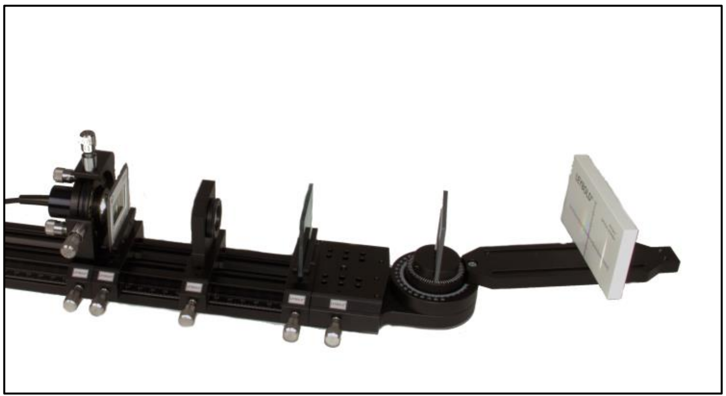

Optical Filter

Objects of the experiment

- Investigation of absorption and Lambert-Beer’s Law
- Observing colour filter high and low band
- Investigation of an interference filter

Principles

a) Absorption and Lambert-Beer’s law

A beam of light propagates in a vacuum without any change in its intensity or polarization state. By interposing a plate or filter into the beam it causes several distinct effects.

First, the plate or filter can convert some of the energy contained in the beam into other forms of energy such as heat. This phenomenon is called **absorption**.

Second, it extracts some of the incident energy and scatters it in all directions at the frequency of the incident beam. This phenomenon is called **elastic scattering** and, in general, gives rise to light with a polarization state and direction different from that of the incident beam.

As a result of absorption and scattering, the energy of the incident beam is reduced by an amount equal to the sum of the absorbed and scattered energy. This reduction is called **extinction**. The extinction rates for different polarization components of the incident beam can be different. This phenomenon is called **dichroism** and may cause a change in the polarization state of the beam after it passes the plate or filter.

Transmittance is the relationship between the intensity of light that is transmitted once it has passed through the plate or filter and the original intensity of light. This is expressed in following formula

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

where I_0 is the intensity of the incident light beam and I is the intensity of the light coming out of the plate or filter. Transmittance is the relative percent of light passed through the plate or filter. Thus, if half the light is transmitted, we can say that the plate or filter has a 50 % transmittance.

The relations between transmittance (T) and absorption (A) can be expressed by following formula:

$$A = \log_{10}\left(\frac{1}{T}\right)$$

Consider the plate as a solution of a chemical species that absorbs light of a particular wavelength. There are two interesting situations.

First, if a beam of light of the appropriate wavelength passes through a fairly dilute solution, the photons will encounter a small number of the absorbing chemical species, so we might expect a high % transmittance and a low absorbance. Alternatively, if the same beam of light passes through a highly concentrated solution, the photons will encounter a large number of the absorbing chemical species, and we might expect a low % transmittance and a high absorbance. Thus absorbance is proportional to the concentration of the sample.

Secondly, if the beam of light travels through a solution for a long way there will be a low % transmittance and a high absorbance; whereas, if the beam passes only a short way through the solution there will be a high % transmittance and a low absorbance. These two considerations lead to the following proportionality:

$$A \propto k \times l \times c$$

Where k is the proportionality constant, l the path length and c the concentration of the absorbing material. When the path length is measured in centimeters, and the concentration of the absorbing species is measured in Molarity, the proportionality constant is called the Molar Absorptivity ε and the proportionality reduces to the **Lambert-Beer’s Law:**

$$A = \varepsilon \times l \times c$$

b) Optical filter

Optical filters make it possible to precisely select a specific band of wavelengths or intensity within an optical system. Optical filters are based on interference, diffraction, or absorption, and they are used in fixed and in tunable filters. The absorption profiles of various color glasses are dependent upon the type and amount of colorant material and base glass composition.

Bandpass filters transmit a band of wavelengths ranging from less then a nanometer to hundreds of nanometers in width while blocking adjacent wavelengths. The passband range of

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a bandpass filter is often described using a center wavelength together with the full width at half maximum (FWHM).

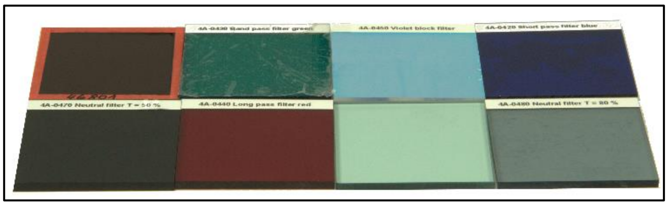

Fig. 1: Top: Infrared band pass filter, bandpass filter green, violet block filter, short pass filter blue. Bottom: Neutral filter 50%, long pass filter red, infrared filter, neutral filter 80%

The optical filter used in this experiment are shown in Fig. 1. The transmittance of the filters has been measured and are presented in the attachments.

c) Interference filter

An optical interference filter is built up of thin discrete layers of materials with various optical properties. When two reflective stacks are joined by a thin-film spacer layer, the reflective stacks create a Fabry-Perot interferometer.

Fig. 2: Interference filter at 550 nm

The Fabry-Perot interferometer consists two high-reflectance multilayers in which successive reflections create multiple beam interference fringes. The simplest design is the flat mirror cavity shown in Fig. 3.

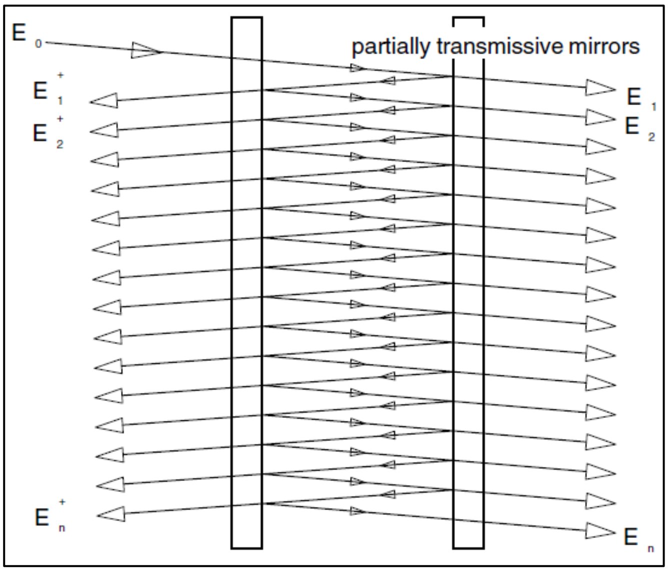

Fig. 3: Fabry-Perot's multi beam interferometer

Multiple interference in the space layer causes the filter output spectral characteristic to peak sharply over a narrow band of wavelengths that are multiples of the $\lambda/2$ spacer layer. Thus, the simple Fabry-Perot interference filter is used exclusively as a band-pass filter.

An interference filter should be illuminated with collimated radiation normal (perpendicular) to the surface of the filter. The central wavelength will shift slightly to a lower wavelength if the illuminating radiation is not normal to the filter. A deviation of less than 3 degrees results in a negligible wavelength shift. At large deviations, the wavelength shift is significant, transmittance decreases and the shape of the passband changes. When noncollimated radiation impinges on the filter, the result is similar to that stated above. In this case, the effect is dependent on the cone angle of the illuminating radiation. Varying the angle of incidence from normal can be used to “tune” an interference filter within a limited wavelength range.

d) Diffraction grating

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.

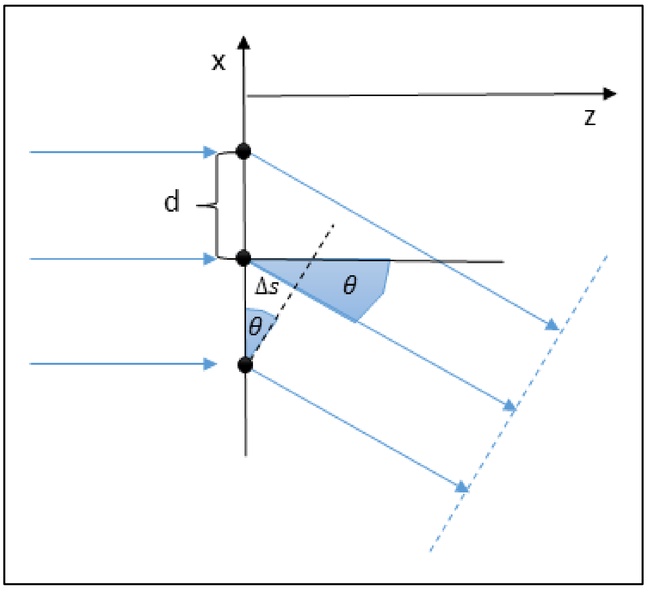

Fig. 4: Principle of diffraction. Calculating the optical path difference Δs.

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. 4. 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:

$$d\sin\theta = m\lambda, \quad m = 0, \pm1, \pm2, \ldots$$

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.

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.

Experiments

To visualize and measure the properties of absorptions and optical filters these experiments are presented:

Experiment 1:

In this experiment the diffraction of a 600 lines/mm grating is investigated by using different optical filters.

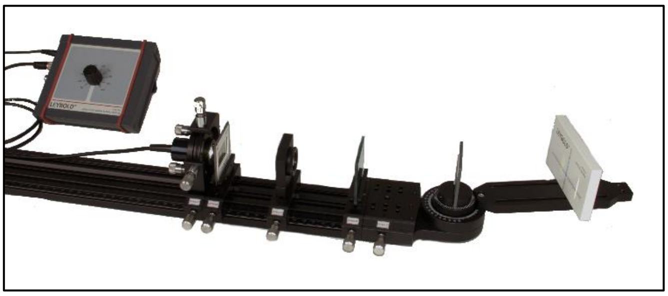

Fig. 5: Setup to measure the diffraction angle

Setup on Bench:

1	Profile rail, 500 mm	........474 5442
1	Swivel Unit with Carrier	........474 121
1	Adaptive Power Supply	........474 301
1	Adjustment holder, 4 axes, with stop ang	......474 2112
1	LED Lamp, White	........474 5411
1	Diaphragm with 3 single slits	........469 91
1	Plano-Convex Lens f = 60 mm	........474 5217
2	Filter Plate Holder	........474 107
1	Adjustment Holder 1 inch, left	........474 213
1	Interference Filter 550 nm	........474 5289
1	Optical filters, Set of 8	........474 5262
1	Transmission Grating, 600 lines/mm	........474 5302
1	Optical Screen with XY Scale	........474 6417

On the bench, the LED Lamp is put into the adjustment holder. Close to the right of it set a filter plate holder with the plate with slits into the beam. For this experiment use slit A, as shown in Fig. 6. Next, set the swivel unit with carrier on the bench in straight direction ($\theta = 0°$) and place the optical screen with XY scale at the end of it. Insert the transmission grating with 600 lines/mm to the middle of the swivel unit.

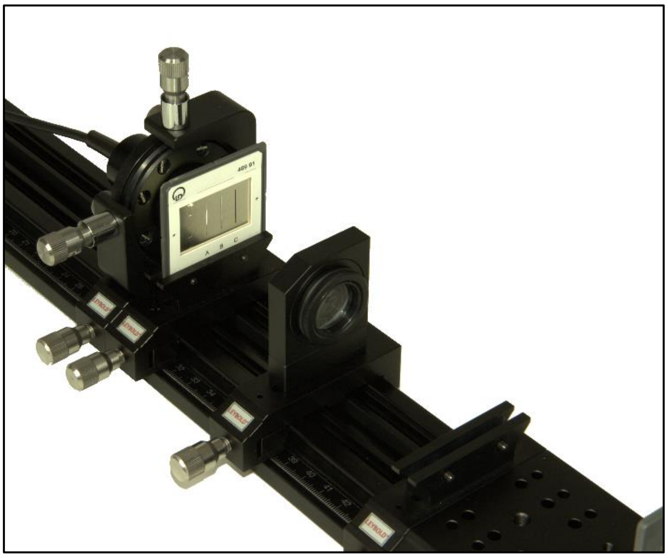

Fig. 6: Setup for setting up the slit in front of the LED lamp.

At this point insert the lens with carrier and focus the lens ($f = 60$ mm) so that at the optical screen a sharp image of the slit appears.

Now turn the swivel unit so that the y axis of the optical screen is in the middle of a color line, as shown in Fig. 7.

Fig. 7: Turning the swivel unit so that the y axis is in the middle of a coloured line.

Insert now the different color filter in the holder to measure the lines more precisely. Note that the glass infrared filter is a bit thicker than the other filters. Therefore loose the small screws at the holder a little bit.

For the interference filter 550 nm the adjustment holder 1 inch is needed, as shown in Fig. 8.

Fig. 8: Setup with interference filter 550 nm in adjustment holder 1 inch.

Insert the interference filter 550 nm with adjustment holder 1 inch directly after the lens. Watch out that the inference filter is normal to the beam. If not so, use the screws at the adjustment holder to tilt the filter in the right position. Turning the interference filter should move the green line to lower wavelengths.

Results:

The measured angles are listed in the following table.

Line	**Angle θ *in* °**
Blue	15
Green	19
Yellow	20,5
Red	22

With the given numbers of slits per mm (600 lines/mm), we can calculate the grating constant:

$$d = \frac{0.001}{600}\,\mathrm{m} = 1.67 \times 10^{-6}\,\mathrm{m}$$

The colored lines are maxima of the first order so that the wavelength can be calculated by the following formula:

$$\lambda = d \sin\theta$$

This leads to the following table

Line	**λ in nm**
Blue	431
Green	543
Yellow	584
Red	624

Experiment 2:

In this experiment the intensities, transmittance and absorption of different optical filters by using a 600 lines/mm grating is investigated

Fig. 9: Setup to measure the intensities using a NIR Lamp

Setup on Bench:

1 Profile rail, 500 mm 474 5442
1 Swivel Unit with Carrier 474 121
1 Adaptive Power Supply 474 301
1 Adjustment holder, 4 axes, with stop ang 474 2112
1 LED Lamp, White 474 5411
1 Plano-Convex Lens f = 60 mm 474 5217
2 Filter Plate Holder 474 107
1 Adjustment Holder 1 inch, left 474 213
1 Interference Filter 550 nm 474 5289
1 Optical filters, Set of 8 .... 474 5262

1 Transmission Grating, 600 lines/mm 474 5302
2 Mounting Plate C25 with Carrier 20 mm........474 209
1 Photodetector signal conditioning box 474 306
1 Plano-Convex lens f = 40 mm 474 5216
1 Si PIN Photodetector 474 321
1 Digital multimeter DMM 121 ....531 173
1 Screened cable, BNC/4 mm 575 24

Replace the optical screen with Si PIN Photodetector on the mounting plate C25. Set the other lens ($f = 40\,\mathrm{mm}$) with mounting plate so that the focus is on the window of the photodetector. At the end of the bench the photodetector is connected 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.

Measure the intensities of the lines with and without the optical filters.

Results:
In the following tables the measured intensities are listed. Thereby also the zero order has been measured.

Table 1: Intensities without filter

Line	Intensity in mV
0°	627
Blue	26.5
Green	69.4
Yellow	78.7
Red	65.1

To calculate the transmittance and the absorption the formulas in section Absorption and Lambert-Beer’s law are used.

Table 3: Intensities with longpass filter red

Line	Intensity in mV	T in %	A
0°	179.3	28.6	0.57
Red	17.8	27.3	0.56

Table 4: Intensities with bandpass filter green

Line	Intensity in mV	T in %	A
0°	91.6	14.6	0.84
Blue	5.1	19.2	0.72
Green	11.5	16.6	0.78
Yellow	13.0	16.5	0.78

Table 5: Intensities with violet block filter

Line	Intensity in mV	T in %	A
0°	170.3	27.2	0.57
Blue	8.6	32.5	0.49
Green	8.4	12.1	0.92
Yellow	15.1	19.2	0.71

Table 6: Intensities with short pass filter blue

Line	Intensity in mV	T in %	A
0°	13.9	13.9	0.86
Blue	4.0	15.1	0.82
Green	9.5	13.7	0.86

Table 7: Intensities with interference filter 550 nm

Line	Intensity in mV	T in %	A
0°	17.5	2.8	1.55
Green	3.9	5.6	1.25

Table 8: Intensities with IF block filter

Line	Intensity in mV	T in %	A
0°	398.2	63.5	0.20
Blue	18.2	68.3	0.17
Green	43.2	62.2	0.21
Yellow	54.5	69.3	0.16
Red	41.9	64.4	0.19

Table 9: Intensities with infrared band pass filter

Line	Intensity in mV	T in %	A
0°	154.4	24.6	0.61
Red	10.5	16.1	0.79

Table 10: Intensities with neutral filter T=80%

Line	Intensity in mV	T in %	A
0°	335	53.4	0.27
Blue	12.1	45.7	0.34
Green	22.7	32.7	0.49
Yellow	39.4	50.1	0.30
Red	37.4	57.5	0.24

Table 11: Intensities with neutral filter T=50%

Line	Intensity in mV	T in %	A
0°	116.2	18.5	0.73
Blue	5.2	19.6	0.71
Green	10.5	15.1	0.82
Yellow	12.7	16.1	0.79
Red	11.4	17.5	0.76

Experiment 3:

In this experiment the diffraction of a 600 lines/mm grating is investigated by using different optical filters

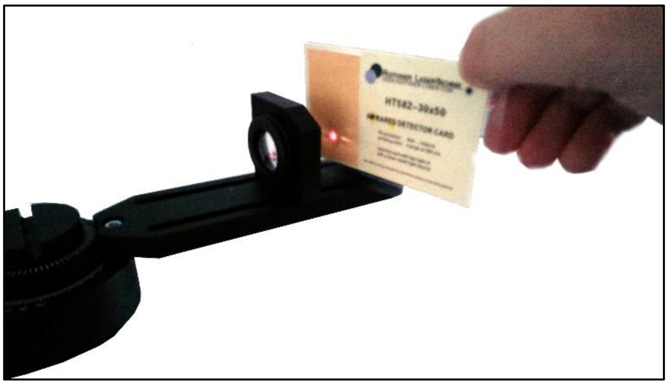

Fig. 10: Focusing the NIR light on to the photodetector via an infrared card.

Setup on Bench:

1	Profile rail, 500 mm	........474 5442
1	Swivel Unit with Carrier	........474 121
1	Adaptive Power Supply	........474 301
1	Adjustment holder, 4 axes, with stop ang	.....474 2112
1	LED Lamp NIR in C25 housing	........474 5416
1	Plano-Convex Lens f = 60 mm	........474 5217
2	Filter Plate Holder	........474 107
1	Adjustment Holder 1 inch, left	........474 213
1	Interference Filter 550 nm	........474 5289
1	Optical filters, Set of 8	........474 5262
1	Transmission Grating, 600 lines/mm	........474 5302
2	Mounting Plate C25 with Carrier 20 mm	........474 209
1	Photodetector signal conditioning box	........474 306
1	Plano-Convex lens f = 40 mm	........474 5216
1	Si PIN Photodetector	........474 321
1	Digital multimeter DMM 121	........531 173
1	Screened cable, BNC/4 mm	........575 24

The setup on the bench is the same as in experiment 2. Replace the LED white with the NIR Lamp. To focus the NIR light exactly on the photodetector an infrared card (4744025) can convert the infrared dot into visible light (shown in Fig. 10.). Therefore place the first lens so that by moving the infrared card behind this lens from one side to the other the size of the dot does not chance. Set the other lens on the end of the bench. Move the second lens so that the focus of the dot is on the window of the photodetector, as shown in Fig. 10.

Fig. 11: NIR Lamp with infrared filter.

Measure the intensity of the NIR lamp with and without the optical filters. With the infrared card it is possible to find the first diffraction order. Note that the room should be dark, because the intensities of the first order is much lower than at zero order.

Results:

In the following table the measured intensities of the zero and first order without filter is listed.

Table 12: Intensities of the NIR lamp

Line	Intensity in V
0°	6.01
29°	26.5

This leads to following wavelength of the NIR lamp

$$\lambda = 8.08 \times 10^{-7}\ \mathrm{m}$$

The intensities with the different filters has been measured.

Table 13: Intensities of the NIR lamp with different filters

Filter	Intensity in V	T in %	A
without	5.94		
Red	5.32	89.6	0.05
Green	2.99	50.3	0.30
Blue	4.72	79.5	0.10
UV	2.73	46.0	0.34
IR Block	0.013	0.2	2.66
IR Pass	5.44	91.6	0.04
T = 50 %	1.90	32.0	0.50
T = 80 %	4.04	68.0	0.17
550 nm	0.0001	0.002	4.77

Experiment 4:

In this experiment the transmittance of the optical filter at 550 nm is investigated.

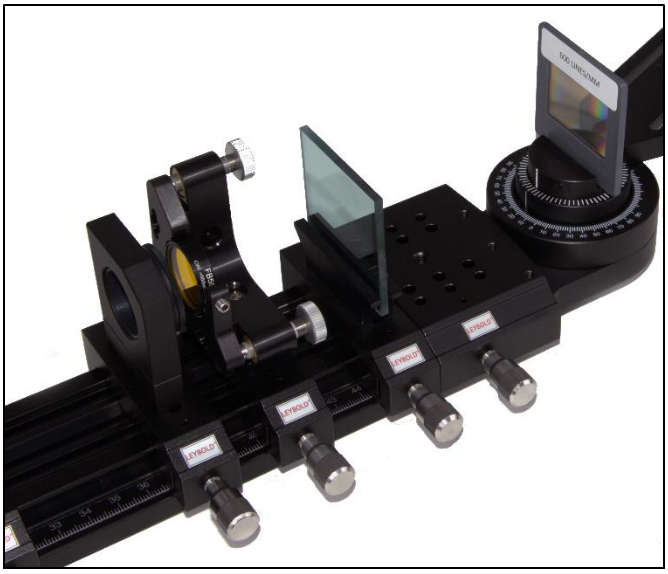

Fig. 12: Setup with interference filter 550 nm plus an optical filter.

Setup on Bench:

1	Profile rail, 500 mm	........474 5442
1	Swivel Unit with Carrier	........474 121
1	Adaptive Power Supply	........474 301
1	Adjustment holder, 4 axes, with stop ang	.....474 2112
1	LED Lamp, White	........474 5411
1	Plano-Convex Lens f = 60 mm	........474 5217
2	Filter Plate Holder	........474 107
1	Adjustment Holder 1 inch, left	........474 213
1	Interference Filter 550 nm	........474 5289
1	Optical filters, Set of 8	........474 5262
1	Transmission Grating, 600 lines/mm	........474 5302
2	Mounting Plate C25 with Carrier 20 mm	........474 209
1	Photodetector signal conditioning box	........474 306
1	Plano-Convex lens f = 40 mm	........474 5216
1	Si PIN Photodetector	........474 321
1	Digital multimeter DMM 121	........531 173
1	Screened cable, BNC/4 mm	........575 24

Replace the NIR lamp with the LED lamp white and place the adjustment holder 1 inch with the interference filter 550 nm directly behind the first lens. Behind the adjustment holder set the filter plate holder. Refocus the second lens so that the spot covers the whole entrance window of the photodetector.

Measure the intensities with and without the set of 8 optical filters.

Table 13: Intensities with interference filter and different optical filters

Filter	Intensity in mV
without	127.8
Red	1.2
Green	36.6
Blue	1.4
UV	5.2
IR Block	104.3
IR Pass	0.9
T = 50 %	21.8
T = 80 %	64.8

In the attachments the transmittance of the optical filters are completely measured and shown.

Attachments

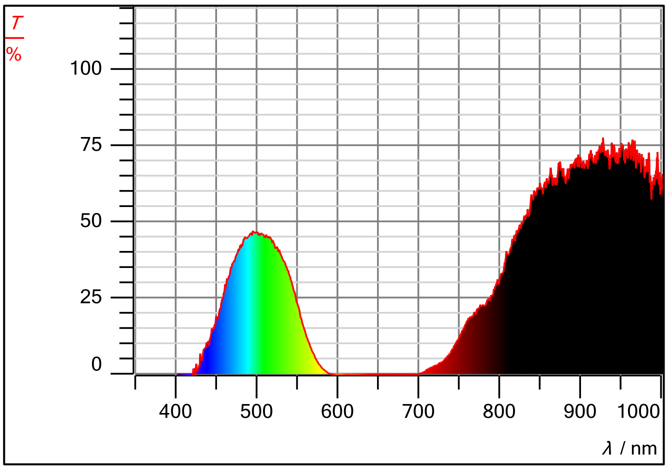

Fig. 13: Transmittance of band pass filter green.

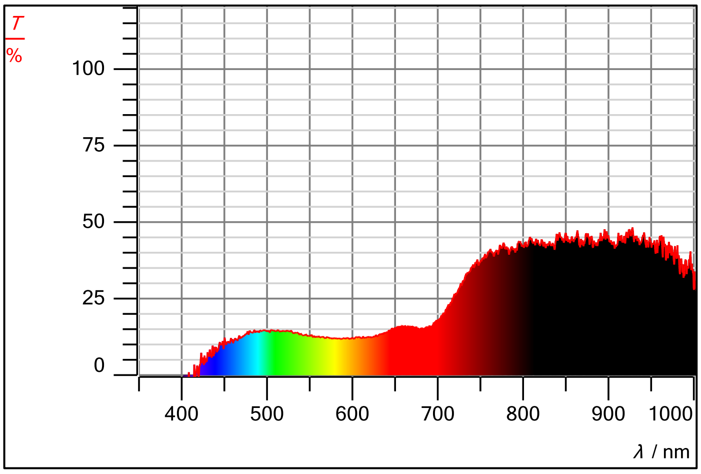

Fig. 16: Transmittance of neutral filter 50%

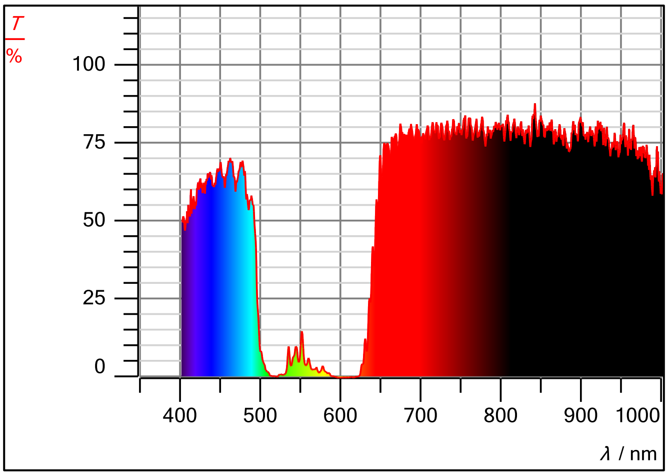

Fig. 14: Transmittance of violet block filter

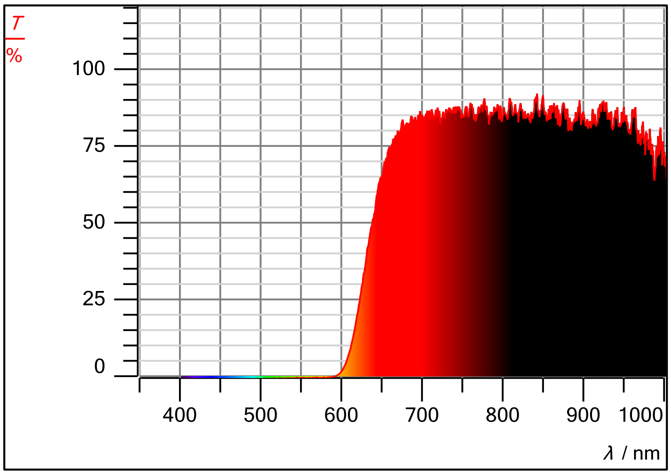

Fig. 17: Transmittance of long pass filter red

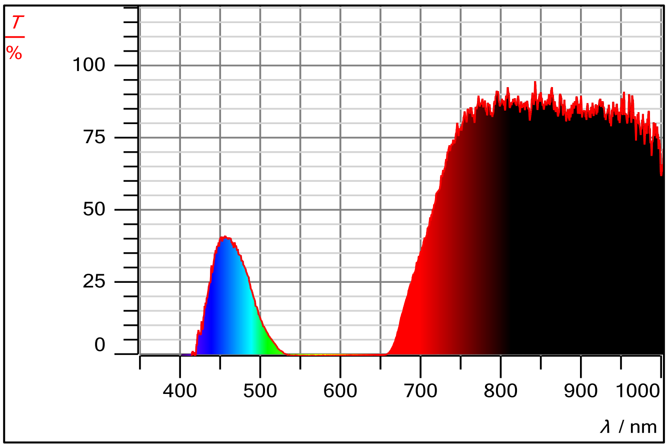

Fig. 15: Transmittance of short pass filter blue

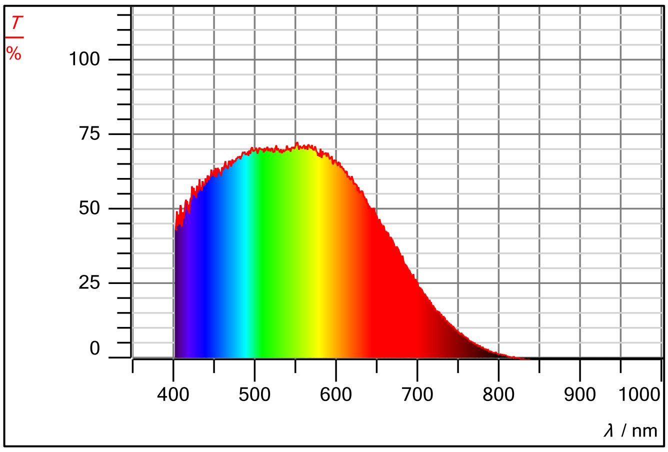

Fig. 18: Transmittance of infrared block filter

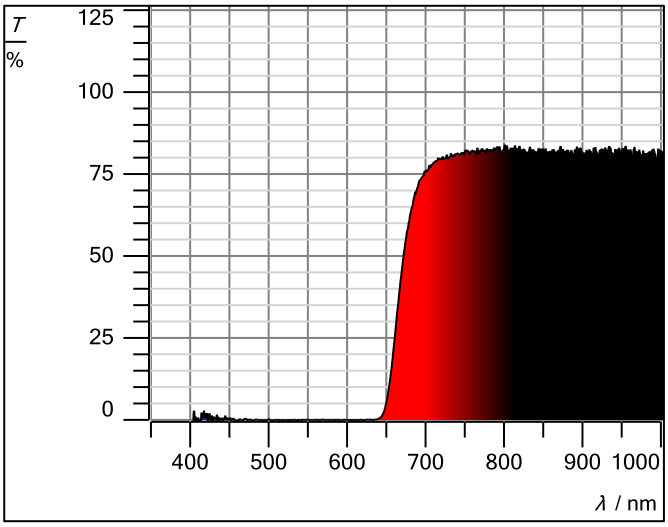

Fig. 19: Transmittance of an infrared pass filter.

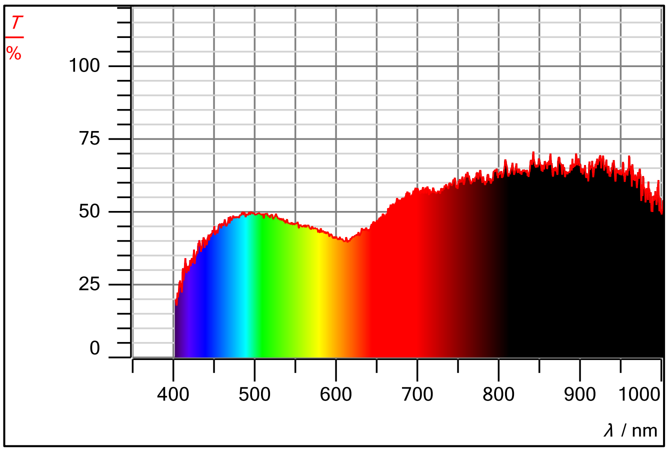

Fig. 20: Transmittance of neutral filter 80%

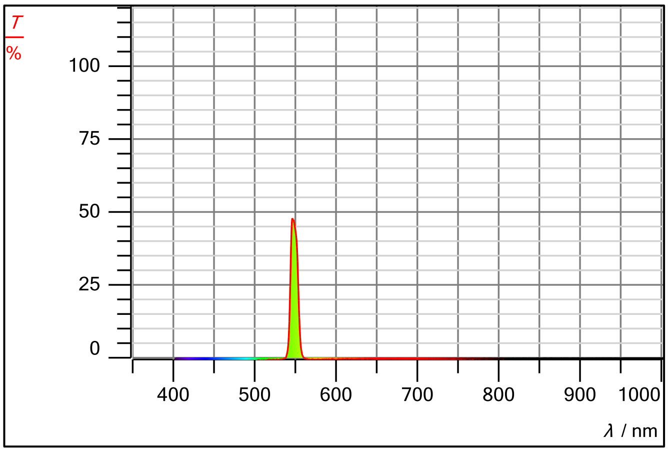

Fig. 21: Transmittance of interference filter 550 nm

Apparatus

1	Plano-Convex lens f = 40 mm	.... 474 5216
1	Plano-Convex Lens f = 60 mm	.... 474 5217
1	Interference Filter 550 nm	.... 474 5289
1	Optical filters, Set of 8	.... 474 5262
1	Transmission Grating, 600 lines/mm	.... 474 5302
1	Filter Plate Holder	.... 474 107
1	Optical Screen with XY Scale	.... 474 6417
1	Photodetector signal conditioning box	.... 474 306
1	Si PIN Photodetector	.... 474 321
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	LED Lamp NIR in C25 housing	.... 474 5416
1	Profile rail, 500 mm	.... 474 5442
1	Swivel Unit with Carrier	.... 474 121
1	Mounting plate 40, C25	.... 474 6411
2	Mounting Plate C25 with Carrier 20 mm	.... 474 209
1	Adjustment holder, 4 axes, with stop ang	..... 474 2112
1	Adjustment Holder 1 inch, left	.... 474 213
1	Transport and Storage Box #01	.... 474 251
1	Manual Optical Filter	.... 474 7216