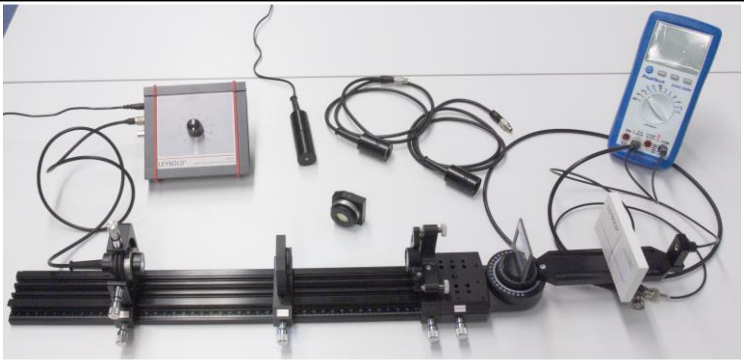


LED and Laser Diode

Objects of the experiment

- Investigate the optical spectra of LED and laser light sources
- Investigate other properties of these sources like polarization and spatial emittance

Safety notes

This experiment uses a Laser. According to EN 60825 it is rated class 3A .

474 5420:

Laser Class 3A, red 635 nm, cw, < 5 mW "CAUTION. Laser Radiation. Do not stare into beam or view directly with optical instruments."

This experiment uses LEDs. According to EN 62471 some are rated class RG3.

474 5411:

LED RG2, white, cw "CAUTION. Possibly hazardous optical radiation emitted from this product. Do not stare at operating lamp. May be harmful to the eye"

474 5412:

LED RG2, red, cw "CAUTION. Possibly hazardous optical radiation emitted from this product. Do not stare at operating lamp. May be harmful to the eye"

474 5415:

LED RG3, blue, cw, "WARNING. Possibly hazardous optical radiation emitted from this product. Do not look at operating lamp. Eye injury may result"

Safety precautions are necessary. Please check with local regulations. Typically the use requires a safety sign and maybe a warning lamp that is on when the laser is activated and it might also be necessary to do and document a risk assessment. In some places it might be necessary to apply for a license or notify the relevant authorities.

Germany: According to OStrV it is necessary to inform the "Gewerbeaufsichtsamt" and the workers' insurance "Berufsgenossenschaft" 14 days prior to startup for Lasers > class 2.

Misuse of lasers and LEDs poses a health risk for the eyes.

Do not operate the devices outside parameters specified in the manual.

People using the laser must be properly trained and students must be supervised.

As a general guidance, the user is advised to:

- Check the laser and LEDs for damages before use
- Never to look into the laser beam
- Do not stare at the LEDs of RG2
- Do not look at the LEDs of RG3
- Take necessary measures that no people or animals can accidentally enter the beam area
- Do not direct the beam on reflecting surfaces or into public areas
- Do not work close to the light path with reflecting tools
- Take off all jewelry and wristwatches when working with the laser to avoid reflections
- While placing or removing optical parts in the light path, switch off the laser or cover its exit
- Use laser protection glasses or laser adjustment glasses where necessary
- Supervise students by trained personnel when they work with the laser system
- Use the laser system only as described in the instruction manuals

Principles

Light emitting diodes and Lasers are two modern ways to produce light. Both are devices where electrical current is used to push electrons and holes into differently doped areas of a semiconductor.

A vintage LED is easy to describe: Electrons moving in the conduction band and holes from the valence band meet in the pn-junction of the device and recombine. During this recombination process, energy is released and a good semiconductor material can radiate this energy as visible light.

The otherwise omnipresent silicon is not able to generate much radiation, the band structure has a so called indirect minimum, preventing the direct recombination of electrons and holes without phonons. In silicon most of the energy is just converted into heat instead of light.

Optoelectronic semiconductor devices come from the so called III-V semiconductors like Gallium Arsenide, GaAs. One element from the third column of the periodic table and one from the fifth are combined. The resulting material has semi-conducting properties and a direct energy gap. The maximum energy released by an electron-hole recombination process is determined by the so called Band-gap of such a material and the maximum energy of the released photons defines the color of the light source. Different elements from the III and V groups can be combined to create the necessary Band Gap to create the colors available today as LEDs.

For example a deep red LED would be using a GaAs Semiconductor, an orange-red LED would need to add some Aluminium for a wider Band gap AlGaAs material. A blue LED needs a much larger Band gap material, like GaN or AlGaN. For an independent adjustment of Band-gap and lattice constant matching AlInGaAs is used. The usual telecom lasers in the infrared are made from InP or InGaAsP.

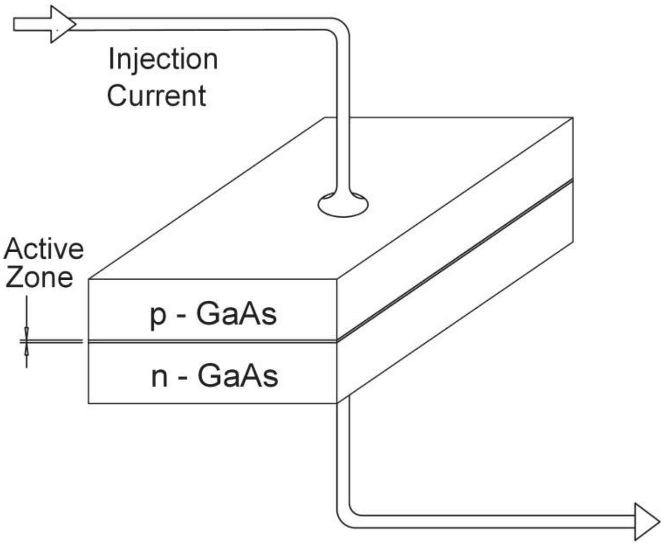
Old green diodes were made from GaP material, but nowadays the much more efficient GaN or InGaN materials are used, sometimes involving intermediate levels in the bandgap to reduce the emitted photon energy.

Due to technological problems of growing high quality films of the nitiride semiconductors, it is necessary to use more than just a pn junction to create a LED. The Nobel price in 2014 was awarded to the creators of the blue LED for this research on microstructured semiconductors.

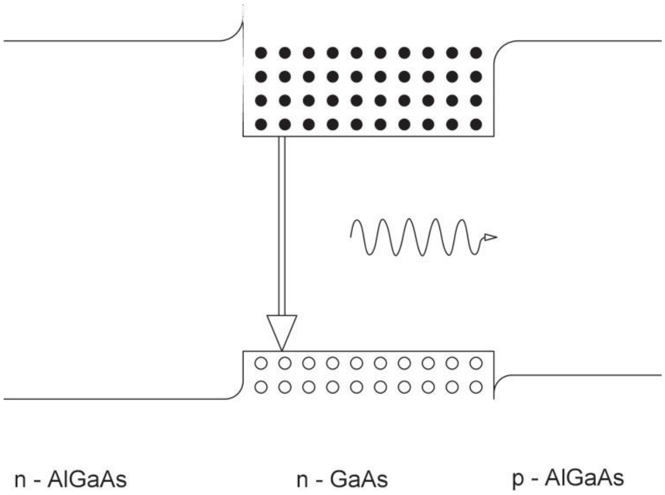
Apart from the III-V semiconductors, several researches investigated II-VI semiconductor structures and created reasonably efficient LEDs, but they did not made a commercial success.

A semiconductor laser is theoretically not much different from a semiconductor LED with two mirrors acting as a resonator, and in fact many laser devices become a LED when the mirrors of the laser resonator are accidentally destroyed by too much optical power.

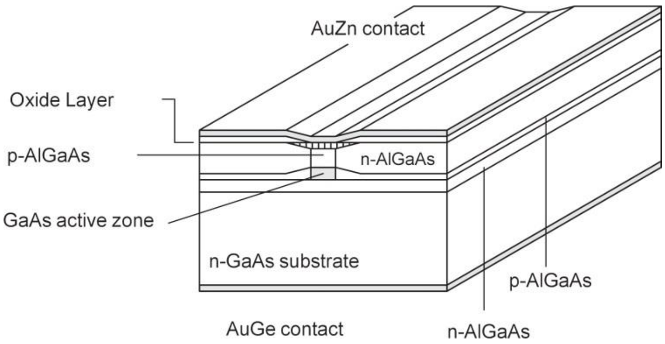
As simple as it may seem, it took about 20 years until people had acquired the necessary technology of coating under extremely pure conditions. It all began in 1962 with the first laser diode, just two years after Maiman had demonstrated the first functional ruby laser. In the course of 1962 three different groups reported more or less simultaneously the realisation of GaAs diode lasers.



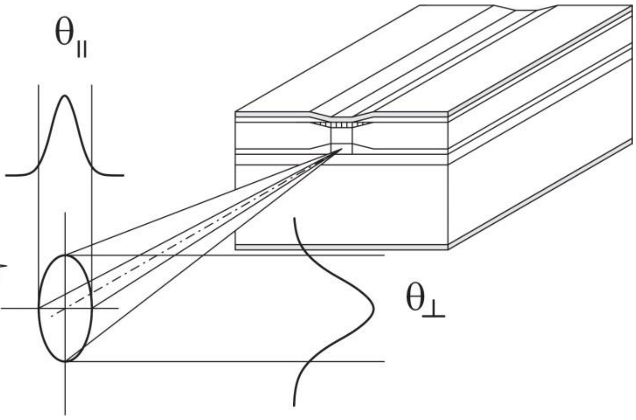
The first laser was basically made of highly doped GaAs. A threshold current of 100 kA/cm² was needed since the GaAs material of those days was not by far as good as it is today regarding the losses within the crystal. Because of thermal conditions the laser could only work at 70 K and in the pulsed mode. During the following years the threshold could be lowered to 60 kA/cm² by improving the crystals but then the use of a heterostructure (Bell Labs. and RCA-Labs.) brought the „breakthrough“ in 1968. The threshold could be lowered to 8 kA/cm² and working in the pulse mode at room temperature. A layer of p conducting AlGaAs is deposited on the p layer of the pn transition of GaAs. The slightly higher band gap of AlGaAs compared to GaAs ensures that a potential barrier is created between both materials in a way that charge carriers accumulate here and the population inversion is increased respectively.



The next step in development was the attachment of a similar layer on the n-side of the crystal. That way the threshold could be lowered once again in 1970. Now it amounted to about 1 kA/cm². Until today nearly all commercially sold laser diodes are built up on the double hetero structure principle.



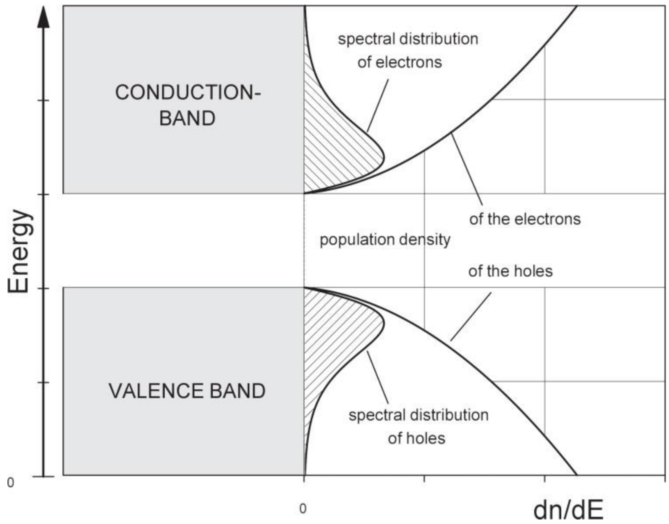
In a laser, we have to have a population inversion for stimulated eimission. In the pn junction, this is done by a large current density to create lots of electrons and holes, which can take part in the process of stimulated emission to amplify light. The semiconductor is put inside a resonator made of two mirrors and the light amplification when it is reflected back and forth is the laser process. Usually, the “mirrors” are just the end facets of the semiconductor crystal where the Fresnel reflection due to the change in index of refraction will act like a semitransparent mirror. Usually some layers of dielectric mirrors are evaporated onto the end facets of the semiconductor.



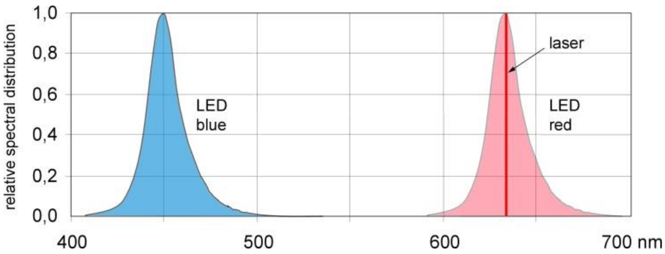
Not only the beam guidance but also the size of the laser mirrors influences the beam geometry. Conventional lasers use very large mirrors compared to the beam diameter. In a laser diode the laser mirror (crystal gap area of the active zone) has a size of about 10 µm x 2 µm, through which the laser beam has „to squeeze" itself. Diffraction effects will be the consequence and lead to elliptical beam profiles. The polarization is parallel to the "junction plane", that is the plane which is passed by the injection current perpendicularly. Light generated by spontaneous emission will be more or less unpolarized and so the ratio of polarization, P⊥ to Pll , depends on the output power since for higher laser power the ratio of spontaneous to stimulated emission is changing.

The divergence angles θ⊥ and θll differ by about 10-30° depending on the type of laser diode. If the beams are extended geometrically into the active medium the horizontal beams will have another apparent point of origin as the vertical beams. The difference between the points of origin is called astigmatic difference. It amounts to about 10 µm for the so called index guided diodes. For the so called gain guided diodes these values are appreciably higher. Modern diodes are mostly index guided diodes. This means that the laser beam is forced not to leave the resonator laterally by attaching lateral layers of higher refractive index to the active zone. At the gain guided diodes the current is forced to pass along a small path (about 2-3 µm width). In this way the direction of the amplification (which is proportional to the current flux) and the laser radiation are determined. At the gain guided diodes the formation of curved wave fronts within the resonator is disadvantageous since they simulate spherical mirrors. In this case higher injection currents provoke transversal modes which will not appear in index guided diodes because of the plane wave fronts. Laser diodes with intensity profiles following a Gauss curve and a beam profile which is only limited by diffraction are called Diffraction Limited Lasers (DFL). They represent the most „civilized" diode lasers. For the time being they are only available for powers up to 200 mW. High power diode lasers have very fissured nearly rectangular intensity profiles.

When we take a look at the resulting optical spectrum, a LED emits a rather wide spectral range of some color. The actual emission, the recombination of electrons and holes, is happening between electrons in the conduction band and holes in the valence band. These are not necessarily located near the edges of each band, so we will see the full width of both bands. Of course, this is related to the temperature of the device via the Boltzmann constant.

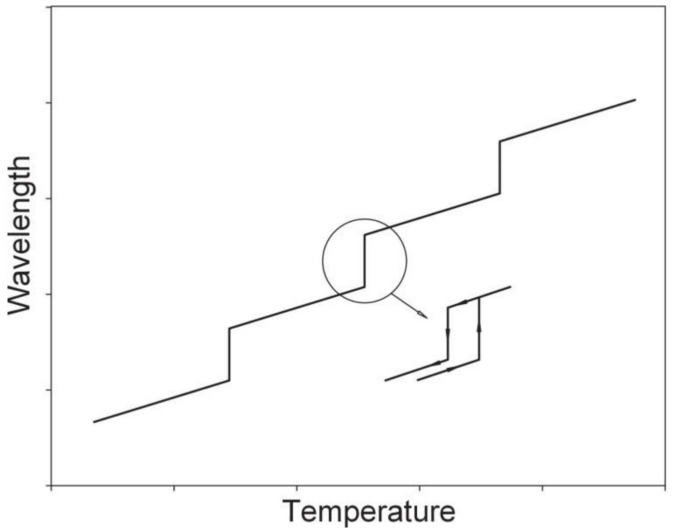


Additionally, the process happens inside the lattice of a semiconductor, so the process will lose energy into phonon excitations.



A semiconductor laser will show a much smaller line width than a LED. First there is a quantization introduced, an integer amount of standing waves has to fit between the two mirrors of the resonator. A cheap multi-mode laser diode will excite several of those modes. A requirement for a laser to work is that the intensity gain for the light during one pass is positive. The gain in the semiconductor has to be larger than all the losses elsewhere. A LED can emit light at any level, but a laser cannot use the full width of the gain profile, but needs some minimum gain. Additionally, there is a thing called mode competition. The most intense modes in the middle of the gain profile will consume a lot of electron-hole pairs (stimulated! emission) and while they are active, the lower gain modes will be reduced in intensity even further. Together, these effects will give the small line width of a laser.

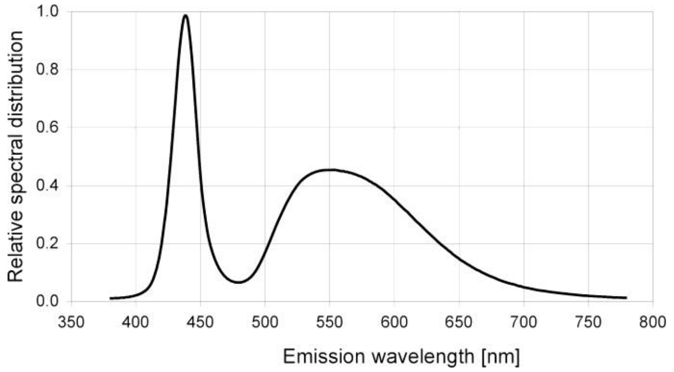
Variations in certain parameters like temperature and current will change the effective index of refraction inside the semiconductor material and change the emitted wavelength accordingly.



The wavelength increases with increasing temperature. The reason for this is that the refractive index and the length of the active zone, respectively the resonator, increase with increasing temperature. Beyond a certain temperature the mode does not fit anymore into the resonator and another mode which faces more favorable conditions will start to oscillate. As the distance between two successive modes is very large for the extremely short resonator (typical 300 µm), the jump is about 0.3 nm. Lowering the temperature gets the laser jumping back in his wavelength. After this the laser must not be necessarily in the departing mode. Applications anticipating the tuning ability of the laser diode should therefore be performed within a jumpfree range of the characteristic line (Fig.21).

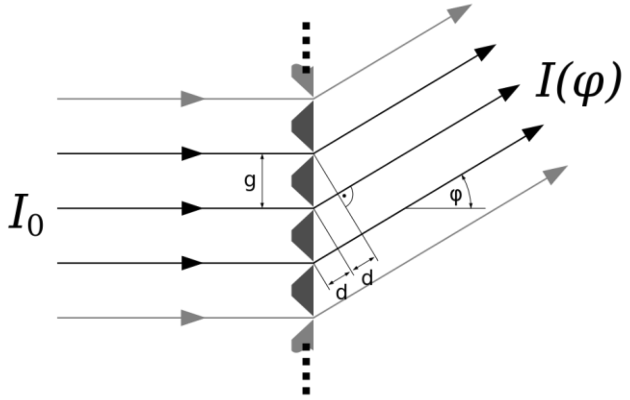
A similar behavior is observed for the variation of the injection current and in consequence for the laser output power. Here the change in wavelength is mainly the result of an increase in the refractive index which again is influenced by the higher charge density in the active zone. A higher output power provokes also a higher loss of heat and an increase in temperature of the active zone. The strong dependence of the current and the output power on the temperature are typical for a semiconductor.

The “white” LED is not a purely semiconductor device. In reality, it is a blue LED coated with a yellowish fluorescent material.



In the optical spectrum we see the blue LED at 440 nm and a broad fluorescence peak from green 500 nm to red 650 nm with a maximum in the yellowish range. Depending on the relation between blue light and yellow fluorescence, the color of the LED can be more cool blue or a warmer yellowish tone.

In the experiments, we will analyze the optical emission properties of several light sources. We use a grating spectrometer to deflect a light ray depending on the wavelength



The incoming light (from the left in the image) is split by the grating. The grating is made of 600 lines per mm, so the distance g in the image is 10^-3 m / 600 = 1,67 µm. At some angles φ which fulfill the condition

$$n\,\lambda = d = g\,\sin(\varphi)$$

there will be constructive interference of the waves passing through each line, because the distance d is an integer multiple of the wavelength.

Experiments

To visualize the properties of Laser and LED radiation, several experiments are presented:

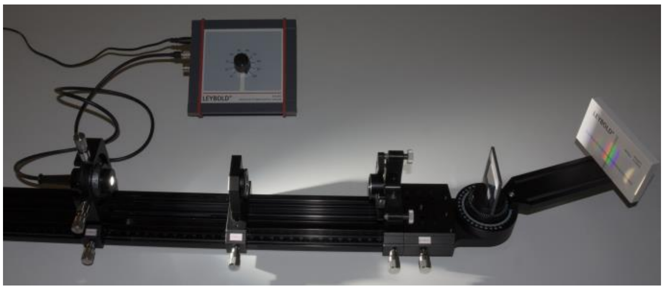
Experiment 1:

Creating spectra from the four light sources involved

Setup on the Bench:

1 DIMO diode laser module, 630 nm (red) 474 5420
1 LED Lamp, White 474 5411
1 LED Lamp, Red 474 5412
1 LED Lamp, Blue 474 5415
1 Adjustment holder, 4 axes, rotary insert 474 2114
1 Cylindrical Lens f = 25 mm, C25 Mount 474 5222
1 Mounting Plate C25 with Carrier 20 mm 474 209
1 Cylindrical Lens f=80 mm, C25 Mount 474 5223
1 Adjustment Holder 1 inch, left 474 213
1 Tranmission Grating, 600 lines/mm 474 5302
1 Swivel Unit with Carrier 474 121
1 Optical Screen with XY Scale 474 6417
1 Adaptive Power Supply 474 301
1 Profile rail, 500 mm 474 5442

On the bench, one of the light sources is put into the holder 474 2114. The grating 474 5302 is put in the slit of the swivel arm 474 121 and the screen is mounted with two screws and the provided hex key to the swivel arm.



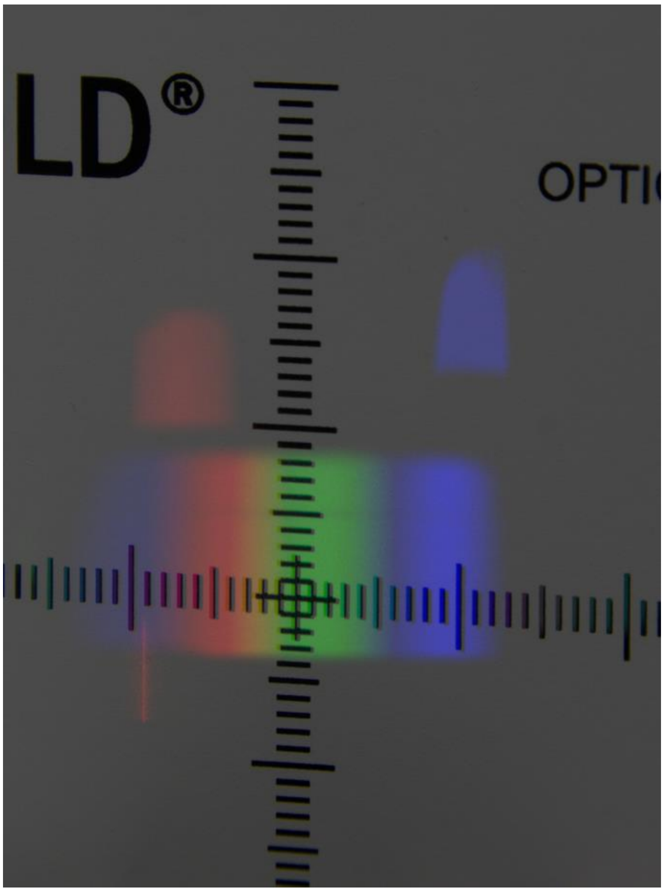
As an initial suggestion, put the lamp at position 14 cm on the bench, the short cylindrical lens 474 5222 oriented for horizontal focusing in a mounting plate 474 209 at position 28,5 cm and the long cylinder lens 474 5223 focusing horizontally in holder 474 213 at position 44 cm.

In this experiment, the two cylinder lenses are oriented the same way, not crossed. In the vertical axis, there is no focusing by the lenses. The two lenses will create a slit like image of the light source on the optical screen. During setup, please optimize the position of the lenses to a sharp image as possible. Initially it is easiest to look at the non-deflected white, producing a white bar of light at angle 0°. This is visible at the right side of the screen in the picture above.

Note: The brightness of the LED emitters can be adjusted by the power supply. For some LED, the power supply will start to switch the lamp on and off above a certain brightness level. This indicates some kind of overload, please reduce the intensity level until no on/off blinking occurs.

The grating will deflect the light according to wavelength, with the red light being deflected more, as seen in the picture above.

The picture below shows a composite photograph of the four possible light sources, from top to bottom blue LED, red LED, white LED and red laser.



As expected, the blue and red LEDs show one single color, but rather broad patches of light. Looking closely at the red LED, the color will change from red to orange on the right hand side of the spectrum. In the photograph, this is barely visible.

The laser instead is just a small line with a width comparable to the width of the undeflected beam.

The white LED shows a more or less continuous spectrum from blue to red. Looking closely, there is a gap between blue and green. The blue light is coming from the LED, while the green to red light is some mixture of fluorescent substances. The red of the white LED does not extend as much to the left as the red LED or the laser. The fluorescent substances in the white LEDs phosphor do not emit longer wavelength red light. Close to the red end is the blue part of the second order spectrum.

The blue LED seems to extend down to 375 nm, but our eyes are not able to see light of that wavelength. The wavelength emitted of such a royal blue LED is indeed around 410 nm and the shorter wavelengths will excite fluorescence in the white paint of the optical screen, so we can indirectly see the UV wavelength. Due to this blue-UV content at high brightness, this LED is to be handled with care. It does not look bright, but it is. Do not look into the beam. Looking at the active LED from more than 40 degree apart of the optical axis for a short time is ok.

After this first quick qualitative look on the different spectra, we can continue to measure the exact angle of deflection.

The swivel unit 474 121 has a scale. Adjust the arm so that the black line in the middle of the screen is at some feature of the spectrum and read the corresponding position of the arm.

From the angle, we can use

$$n\,\lambda = d = g\,\sin(\varphi)$$

with g= 1,67 µm and n=1 in first order to calculate the wavelength.

	Feature	Angle	λ
White LED	Blue Start	15	431 nm
	Blue Maximum	15,5	445 nm
	Blue end	16,5	473 nm
	Cyan Gap		
	Green Start	18	515 nm
	Yellow	20	570 nm
	Red End	22	624 nm
Red LED			
	Red/orange	20	570 nm
	Red End	23	651 nm
Blue LED			
	Start	13	375 nm
	End	14,5	417 nm
Laser			
	Line	22,5	638 nm

To take a closer look at the line width of the blue and red LED, let's calculate the line width in terms of energy:

A wavelength of 570 nm corresponds to 2,1 eV and 651 nm equals 1.9 eV. The difference ist 0.27 eV or about 10 kT (Boltzmann).

For the blue LED, we have a bit more, about 13 kT.

Obviously, this line width does not only come from thermal processes. The injected electrons and holes seem to be not exactly thermalized.

Experiment 2:

Recording spectra from the four light sources involved

Replace the optical screen with the photodetector setup.

Additionally required:

1 Photodetector for Pivot Arm 474 6414
Including
1 BNC T-connector
1 BNC 1 M resistor

1 Digital multimeter 3340 ....531 183
1 Screened cable, BNC/4 mm 575 24

Setup on the Bench:

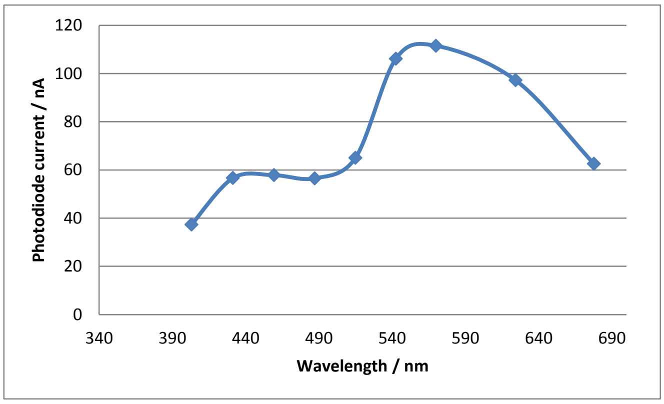
The photodetector is put at the end of the swivel arm and stepwise moved through the spectrum. In the picture above, the colors from blue to red are visualized by a double exposure.

The photodetector is a photodiode without any amplifier. The incoming light creates a current proportional to the light intensity. The photocurrent is this setup is around 100 nA.

Depending on the multimeter ordered, this current can be measured either directly in a low current measurement range. The multimeter shown in the photograph above could only measure in steps of 100 nA. To measure the small currents, a 1 MΩ resistor connected to a BNC-T connector is used. The photocurrent will flow through the resistor and create a voltage drop. A photocurrent of 100 nA will create a voltage drop of 100 mV and this is measured in the 200 mV range of the multimeter. Please note that this multimeter has to have a real high input resistance in the lower mV ranges. Other multimeter might have only 10 MΩ input resistance in parallel to the 1 MΩ resistor, effectively creating 9.1 MΩ resistance.

This way of measurement is possible only for small currents. Whenever the photocurrent exceeds about 150 nA, the resulting voltage drop will create some opposite current through the photodiode. This will generate a large nonlinearity above 150 mV. The later experiments will create more photocurrent and then we can simply measure the current directly in the µA range of the multimeter.

Moving the swivel arm in steps through the spectrum and recording the photocurrent will give a curve like this.



We clearly see the two maxima in the blue and yellow parts of the spectrum and can discuss the same features as with the optical spectrum.

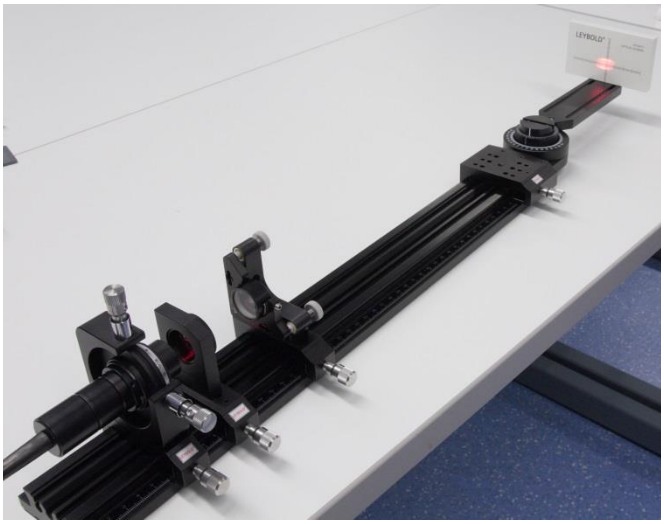
Compared to theory, the blue peak is much smaller than expected. Our photodiode is a simple silicon diode without any optical filter. The efficiency of silicon is not constant across the wavelength. The diode is named BPX61 and a datasheet can be obtained. The sensitivity vs. wavelength is specified there and can be used to correct the recorded data.

Experiment 3:

Laser beam

Required parts

1 DIMO diode laser module, 630 nm (red) 474 5420
1 Adjustment holder, 4 axes, rotary insert 474 2114
1 Plano-Convex lens f = 40 mm, C25 mount ...474 5216
1 Cylindrical Lens f = 25 mm, C25 Mount 474 5222
1 Mounting Plate C25 with Carrier 20 mm 474 209
1 Cylindrical Lens f=80 mm, C25 Mount 474 5223
1 Adjustment Holder 1 inch, left 474 213
1 Swivel Unit with Carrier 474 121
1 Optical Screen with XY Scale 474 6417
1 Profile rail, 500 mm 474 5442



The red laser diode contains no further optics and emits a broad cone of light. Due to the internal structure of the diode, there is a lot of diffraction involved when the laser radiation is emitted from a very tiny optical window having a size not much larger than the wavelength of the radiation.

To produce a real laser “beam” we need some additional optics. First use the planoconvex lens 474 5216.

It is possible to create a small (sub-mm) spot of light on the screen, with some artifacts around it from lens errors.

But moving the screen back and forth will show this is a focal spot, no laser beam. A real laser beam should keep constant diameter in every distance.

Moving the lens closer to the laser (40 mm focus) will create an elliptically shaped beam that is lather large, but fairly constant over distance.

Later on we will measure the exact divergence of the laser beam; the result is 36° x 8° FWMH.

This value can be used to calculate the beam size:

The 8° are the full width of the beam cone, so we have 4° in each direction to the optical axis. After 40 mm focus, the beam is 2* tan (4) * 40 mm = 5,6 mm in diameter.

As FWMH is specified at 50% intensity, the visible beam diameter will be a lot more. But at 10 mm diameter, the laser beam will indeed fade away and we get a constant dimension at this size. Use the ruler on the optical screen to measure.

In the other direction, the laser beam has a much larger divergence, and 2* tan (18)* 40 mm is 26 mm, more than the diameter of the lens. Here the laser beam diameter is limited by the optics used. Nevertheless, the diameter of the beam will not change much with distance.

Using the two cylinder lenses we could create a setup that focusses the laser independently in two dimensions.

Both lenses are placed at their focal lengths in front of the laser and they are oriented orthogonal to each other and the laser is of course aligned to the axes of the lens.

This way we can focus both axis independently and see what happens.

Using the FWMH values we can calculate:

2* tan (4°) * 75 = 10,5 mm

2*tan (18) * 20 = 13 mm

So we would expect a beam sized 10.5 x 13 mm, but since this is the 50% intensity size of the beam, this is not clearly visible. The bright laser will be visible across the whole size of the cylinder lenses provided.

Experiment 4:

Polarization

Required parts

1 DIMO diode laser module, 630 nm (red) 474 5420
1 Adjustment holder, 4 axes, rotary insert 474 2114
1 Cylindrical Lens f = 25 mm, C25 Mount 474 5222
1 Mounting Plate C25 with Carrier 20 mm 474 209
1 Cylindrical Lens f=80 mm, C25 Mount 474 5223
1 Adjustment Holder 1 inch, left 474 213
1 Polarisation analyser 40 mm, VIS 474 6431
1 Swivel Unit with Carrier 474 121
1 Photodetector for Pivot Arm 474 6414
1 Digital multimeter 3340 ....531 183
1 Screened cable, BNC/4 mm 575 24
1 BNC adapter, straight 501 10
1 Profile rail, 500 mm 474 5442

Setup the experiment as seen on the photo

The laser plus both cylinder lenses in crossed orientation create a laser beam.

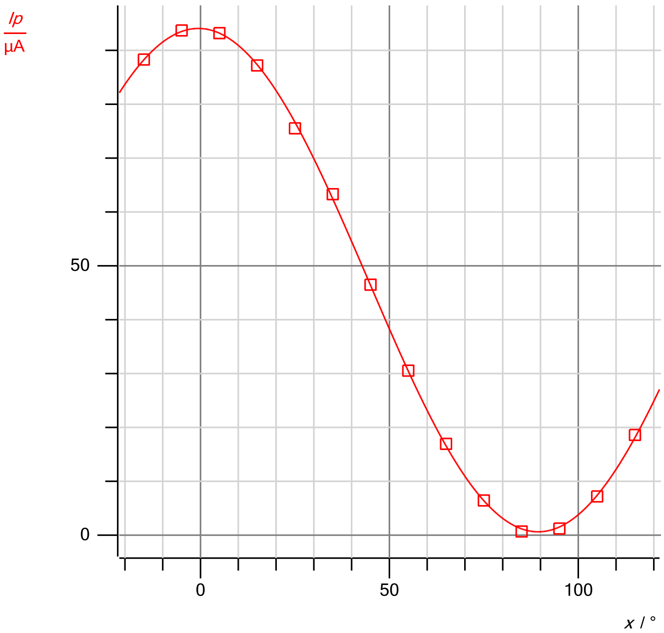
This laser beam passes through the polarization filter and the resulting intensity is measured by the photodiode.

In this experiment, we do have a lot of light intensity on the photodetector, and therefore we can use the µA range of the multimeter directly. Please connect as shown in the photo. The 1M resistor is not used.

Now we put the laser in a defined orientation either horizontally or vertically. Use the provided screwdriver to fasten the screws to hold it into position

The polarization analyzer has a scale and we record the light intensity on the photodetector versus rotation angle of the polarizer.

A typical result could look like this:



The points are measured values and the line is a fit of the function

A*sin(B*x+C)+D

to the measured data, resulting in best fit coefficients

A = 46,724; B = 2,0012; C = 91,114; D = 47,344

From theory, we know that a laser diode has two different axis and we assume a more or less polarized light.

As can be seen, there is a position where the is very few light passing through the analyzer or mathematically spoken parameter A is nearly as big as D, so we see that there is very few light of the other polarization and the laser light is nearly completely polarized.

If the laser would have been oriented perfectly, the parameter C should have been exactly 90, here the laser was put into position with 1° offset.

The parameter B is more or less equal to two, indicating we have a symmetrical image every 180°. The polarization analyzer does distinguish the orientation, but not any positive or negative phase of the light.

Of course the same experiment could be done with the LED devices, but the result would be a constant intensity, indicating no polarization.

Experiment 5:

Angular distribution, diffraction

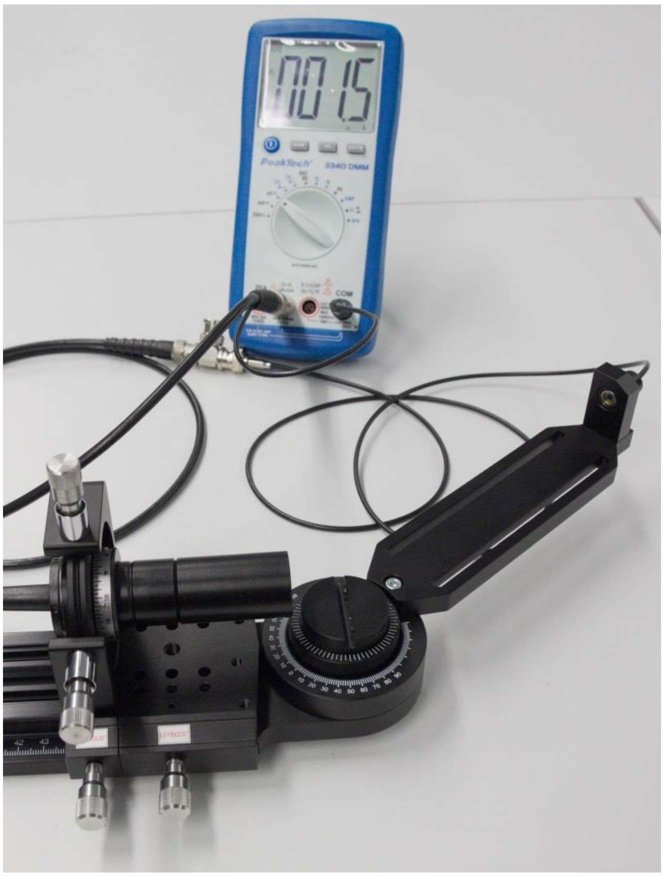
Required parts

1 DIMO diode laser module, 630 nm (red) 474 5420
1 LED Lamp, White 474 5411
1 LED Lamp, Red 474 5412
1 LED Lamp, Blue 474 5415
1 Adjustment holder, 4 axes, rotary insert 474 2114
1 Swivel Unit with Carrier 474 121
1 Photodetector for Pivot Arm 474 6414
1 Digital multimeter 3340 .... 531 183
1 Screened cable, BNC/4 mm 575 24
1 BNC adapter, straight 501 10
1 Adaptive Power Supply 474 301
1 Profile rail, 500 mm 474 5442

The setup looks like the photo below, a light source is positioned more or less in the center of rotation of the swivel arm.

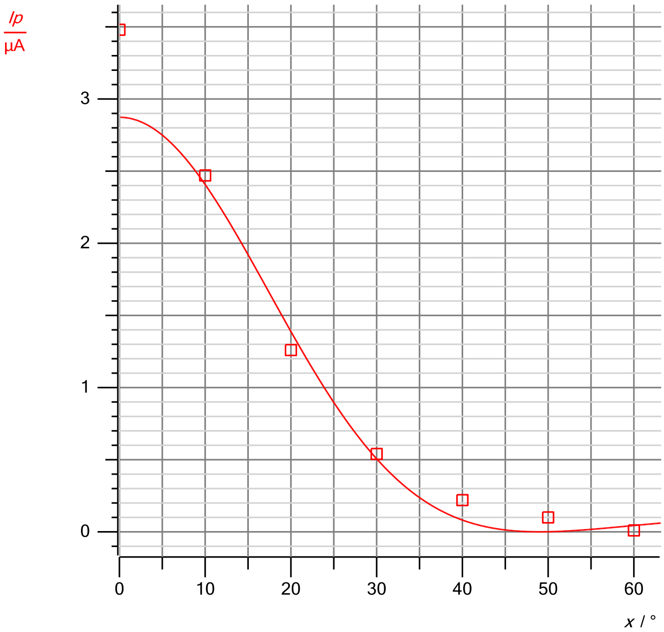
The resulting error of not exactly reaching the center can be neglected.

Please note that we need to read the scale of the swivel arm underneath the light source.



The laser emits nothing like a laser “beam” but a flat cone of light. This is the natural consequence of the microscopic structure of the device involving an active area about the size of a wavelength.

In one axis, we have a rather broad distribution of light



The cause is the diffraction at the exit window. This is just a single slit diffraction, but the slit size is close to a wavelength, so we get a rather large diffraction pattern.

The points are measured values, the curve drawn is a fit to the Fraunhofer diffraction equation

$I(\varphi) = I_0\ sinc^2\left(\frac{180*d}{\lambda}sin\varphi\right)$

with the parameter $\frac{d}{\lambda}$ = 1,3.

So we just measured that one dimension of the laser diodes optical exit window is just 1.3 * 635 nm = 825 nm wide.

Obviously, the fit is not that perfect, as there are several things ignored, it is not an infinitely thin slit, but more a wave-guide.

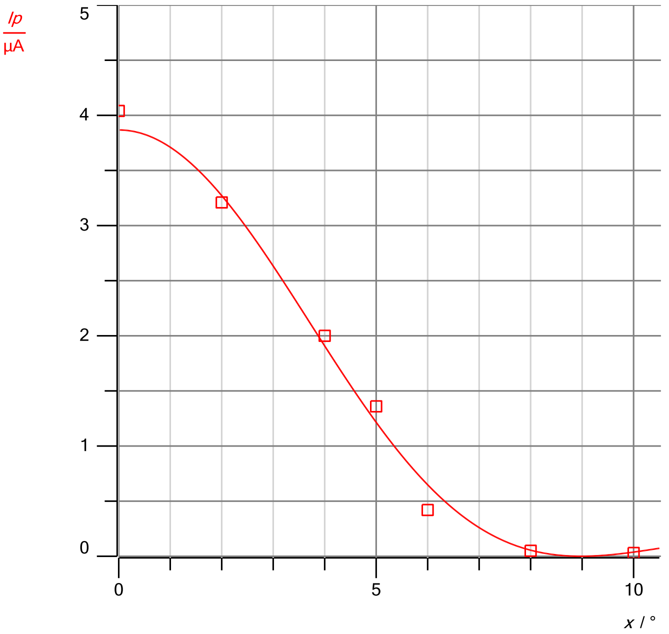
For practical uses, the manufacturer does not specify some diffraction pattern, but simply talks about divergence. Usually such a beam divergence is specified as FWMH, full width at mean height,

In this direction, the laser even emits light beyond the geometric window of the housing, but half the intensity is is used to define the width of the laser beam, which is around 18° in this measurement. The specification would be 36° FWMH in this example.

The datasheet of the diode used specifies

28° minimum, 34° typical and 40° maximum.

The same measurement can be done on the small axis of the laser resulting in a diagram like this:



Again, measurement points and the curve fitted to the Fraunhofer formula.

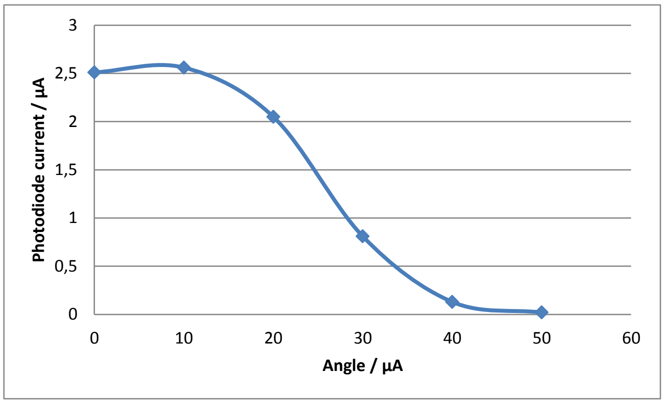
Here we get with the parameter $\frac{d}{\lambda}$ = 6,4 and accordingly a size of the exit window of 4,1 µm.

So we measured from diffraction this laser diode has a 4.1 x 0.825 µm exit window without any microscope.

We see a 50% intensity at 4° or a FWMH value of 8°. The datasheet specifies 6° minimum, 8° typical, 12° max.

The same measurement can be done for the LED sources, but since they are axially symmetric, there are no two axes.

The white LED gives a result like this:



Due to the lens involved, this is not a Lambertian source, but the light intensity falls of at a smaller angle.

This angular distribution got nothing to do with diffraction.

FWMH is about 50°.