

LE-0400 Diodelaser Characterisation

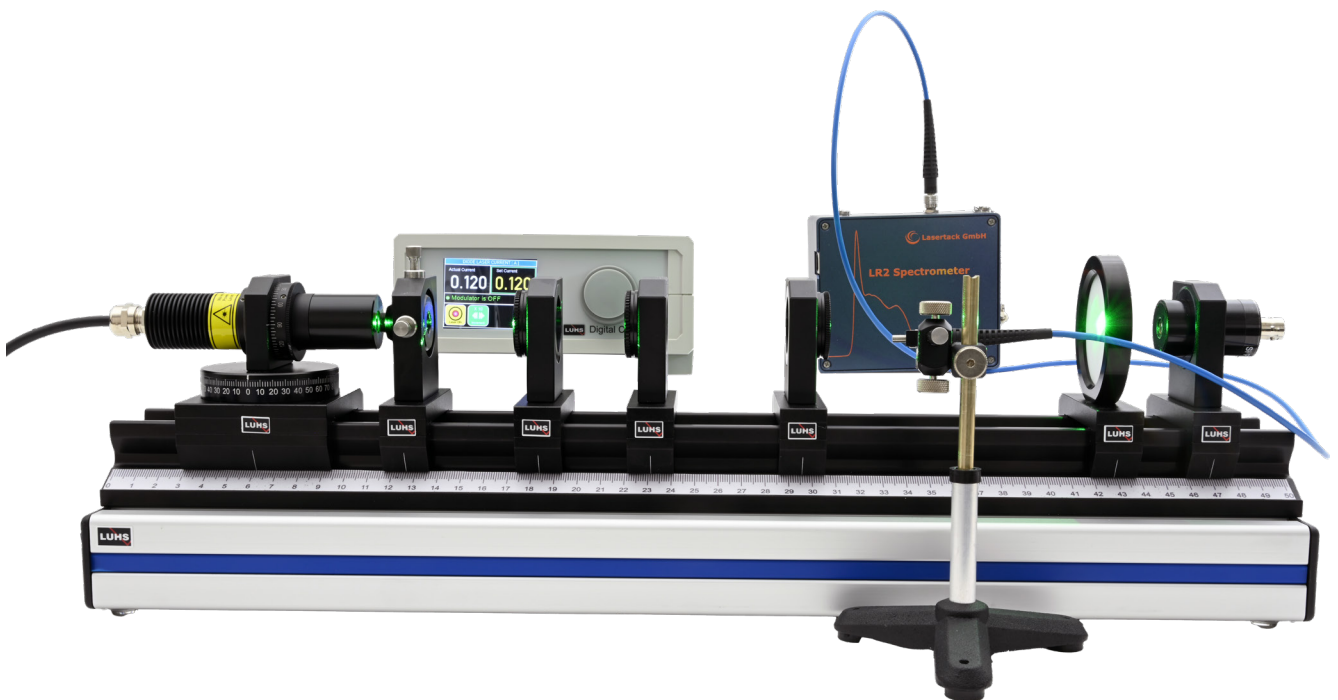
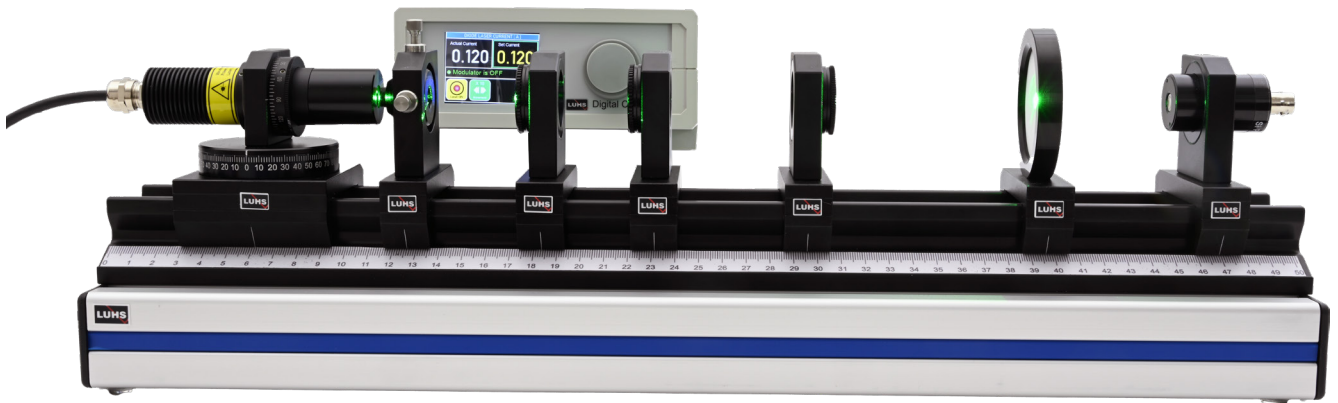


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1.0 Laser diodes

Laser diodes represent a unique category of lasers. They are distinct from “traditional” lasers in two ways:

1. For the classical lasers the laser-active atoms (molecules or ions) are independent of one another and only the same energy levels are used for the laser process. This means in principle that in order to produce a population inversion an infinite number of atoms can contribute (Boltzmann statistics).
2. This is not the case with semiconductor lasers. Here a defined energy level can only be occupied by two active particles (electrons, Pauli principle). But in semiconductors, the wave functions of the individual atoms overlap to form a common energy band and the extent to which the level is occupied follows the Fermi Dirac statistics. When considering the laser process, the transition between the distribution of population in two energy bands instead of two energy levels must be taken into account as for conventional lasers.

Laser diodes do not have any inherently defined emission wavelength, because there are no two discrete energy levels that are responsible for the laser process as with traditional lasers, but rather an energy distribution of electrons in energy bands. The second important difference concerns the propagation of the laser light within the pn zone. The spatial intensity distribution of the laser beam is defined by the laser medium and not by the resonator as for normal lasers. The goal of this experiment is also the understanding and checking of the basic facts. Therefore the difference between a laser with two discrete energy levels and the semiconductor laser with the typical band structure will be discussed in the following.

1.1 The energy band model

Atoms or molecules at large distance (compared to the spatial dimensions) to their neighbours do not notice mutually their existence. They can be considered as independent particles. Their energy levels are not influenced by the neighbouring particles.

The behaviour will be different when the atoms are approached as it is the case within a solid body. Depending on the type of atoms and their mutual interaction the energy states of the electrons can change in a way that they even can abandon „their“ nucleus and move nearly freely within the atomic structure. They are not completely free, otherwise they could leave the atomic structure.

How the „free“ electrons behave and how they are organised will be the subject of the following considerations. From the fundamentals of electrostatics we know that unequal charges attract. Therefore it is easy to imagine that an atomic structure is formed by electrostatic forces.

In the following we will call it „crystal“. However, this model will fail latest when we try to justify the existence of solid Argon just by freezing it sufficiently. Since there is obviously some sort of binding within the crystal structure in spite of the fact that inert gases are neutral there must be additional forces which are responsible for this binding.

To understand these forces we must call on quantum mechanics for help. At the beginning this may be a bit difficult but it simplifies the later understanding. The Hamilton operator and Schrodinger's equation are supposed to be known. But the acceptance of the result of the following expertise on exchange interaction, exchange energy and tunnel effect for the formation of energy bands will be sufficient for further understanding provided quantum mechanics is considered as the background of all.

1.2 The binding of the hydrogen molecule

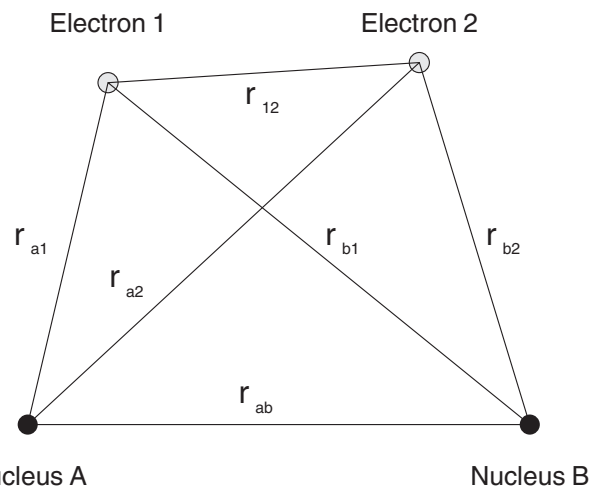


Fig. 1: Interaction of two hydrogen molecules

The total electric potential energy is:

$$U = -e^2 \cdot \left(\frac{1}{r_{a1}} + \frac{1}{r_{b2}} + \frac{1}{r_{b1}} + \frac{1}{r_{a2}} - \frac{1}{r_{ab}} \right) \quad (1.1.1)$$

The following Schrodinger equation has to be solved:

$$\Delta\Psi_1 + \Delta\Psi_2 + 8\pi^2 \frac{m}{h^2} \cdot (E - U) \cdot \Psi = 0$$

For two hydrogen atoms without interaction the total energy will be

$$E = E_0(1) + E_0(2) = 2E_0$$

Correspondingly the eigenfunction ψ is the product of the eigenfunctions of the individual electrons belonging to the nuclei a and b.

$$\Psi_{12} = \Psi_a(1) \cdot \Psi_b(2)$$

Since we can not distinguish between the individual electrons also the following linear combinations are valid eigenfunctions:

$$\Psi_{anti} = \Psi_a(1) \cdot \Psi_b(2) - \Psi_a(2) \cdot \Psi_b(1)$$

$$\Psi_{sym} = \Psi_a(1) \cdot \Psi_b(2) + \Psi_a(2) \cdot \Psi_b(1)$$

At the same time Pauli's principle has to be respected, that means the eigenfunction Ψ_{ant} contains additionally the antiparallel spins ($\uparrow\downarrow + \downarrow\uparrow$) and the function Ψ_{sym} the parallel spins ($\uparrow\uparrow - \downarrow\downarrow$). The electron distribution described by the linear combinations depends also on the distance dependent mutual electrostatic disturbance. As disturbance we have to consider the terms

$$\Delta U = -e^2 \cdot \left(\frac{1}{r_{b1}} + \frac{1}{r_{a2}} - \frac{1}{r_{ab}} \right)$$

which are the reason for the mutual interaction. To get the complete solution we have to add a „disturbance“-term to the undisturbed eigenfunctions ψ_a and ψ_b , as well as to the undisturbed energy. Then Schroedinger's equation will no more be homogenous but inhomogeneous because of the additional „disturbance“-term. As solution we get:

$$E_{sym} = 2E_0 + e^2 \cdot C + e^2 \cdot A$$

$$E_{anti} = 2E_0 + e^2 \cdot C - e^2 \cdot A$$

We see that a term with the constant C representing the Coulomb part and a term with the constant A representing the interaction are added to the undisturbed energy. The exchange energy is based on the fact that electron 1 is localised near to nucleus A at a particular instant and near to nucleus B at another instant. The sign of A can be positive or negative. The energy difference between the two possible energies is just

$$\Delta E = E_{sym} - E_{anti} = 2 \cdot e^2 \cdot A$$

A detailed calculation results in the following relation for C:

$$C = \int \left(\frac{1}{r_{ab}} - \frac{1}{r_{a2}} - \frac{1}{r_{b1}} + \frac{1}{r_{12}} \right) \cdot \Psi_a^2(1) \cdot \Psi_b^2(2) d^3r$$

and for A:

$$A = \int \left(\frac{1}{r_{ab}} - \frac{1}{r_{a2}} - \frac{1}{r_{b1}} + \frac{1}{r_{12}} \right) \cdot \Psi_a(1) \Psi_b(2) \Psi_a(2) \Psi_b(1) \cdot d^3r$$

Under respect of the fact that $\psi_{a2}(1)$ and $\psi_{b2}(2)$, integrated over the whole space represent probability densities which, multiplied by the elementary charge e, provide the total charge density ρ of the electrons 1 or 2 near the nuclei A or B, the constant C can also be written as:

$$e^2 C = \frac{e^2}{r_{ab}} - \int \frac{e^2 \rho_1}{r_{b1}} d^3r_1 - \int \frac{e^2 \rho_2}{r_{b2}} d^3r_2 + \iint \frac{e^2 \rho_1 \rho_2}{r_{12}} d^3r_1 d^3r_2$$

We see that C results out of the attracting or repulsing Coulomb forces. The exchange integral A looks very much like the Coulomb integral. But the electron densities $\psi_{2a}(1)$ resp. $\psi_{2b}(2)$ have been replaced by the mixed terms $\psi_a(1) \psi_b(2)$ and $\psi_a(2) \psi_b(1)$ which are the result of the electron exchange. Here we can summarise as follows: If atoms are mutually approached the states of the undisturbed energy levels split into energetically different states. The number of newly created energy states are corresponding to the number of exchangeable electrons. (Fig. 2).

One of the curves shows a minimum for a particular distance of the atoms. No doubt, without being forced the atoms will approach till they have acquired the minimum of potential energy. This is also the reason for hydrogen to occur always as molecular hydrogen H_2 under normal conditions. The second curve does not have such a distinct property. The curves distinguish in so far as for the binding case the spins of the electrons are anti-parallel. For the

non-binding case they are parallel. It is easy to imagine that an increase of the number of atoms also increases the number of exchangeable electrons and in consequence also the number of newly generated energy levels. Finally the number of energy levels is so high and so dense that we can speak about an energy band. Here it is interesting to compare the action of the electrons with the behaviour of ambassadors.

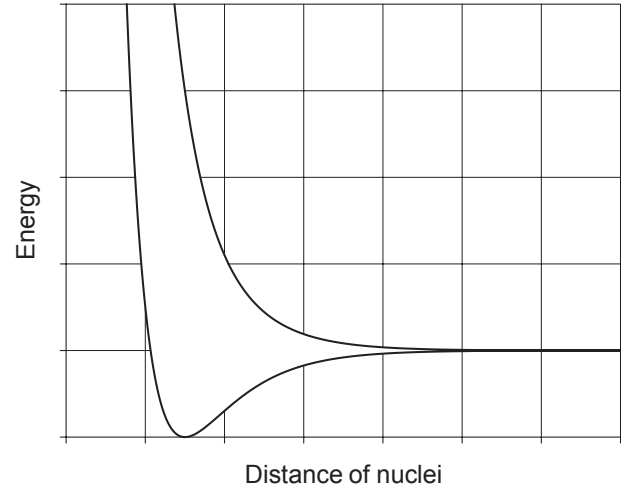


Fig. 2: Potential energy due to interaction of two hydrogen atoms

The electrons in the most outside shell will learn first about the approach of an unknown atom. The eigenfunctions will overlap in a meaningful way. One electron will leave the nucleus tentatively to enter an orbit of the approaching atom. It may execute a few rotations and then return to its original nucleus.

If everything is OK and the spins of the other electrons have adapted appropriate orientations new visits are performed. Due to the visits of these „curious“ electrons the nuclei can continue their approach. This procedure goes on till the nuclei have reached their minimum of acceptable distance. Meanwhile it can no more be distinguished which electron was part of which nucleus.

If there is a great number of nuclei which have approached in this way there will also be a great number of electrons which are weakly bound to the nuclei. Still, there is one iron-rule for the electrons: my energy level can only be shared by one electron with opposite spin (Pauli principle). Serious physicists may now warn to assume that there may be eventually male and female electrons. But who knows.....

Let's return to incorruptible physics.

Up to now we presumed that the atom only has one electron. With regard to the semiconductors to be discussed later this will not be the case. Discussing the properties of solid bodies it is sufficient to consider the valence electrons that means the most outside located electrons only as it has been done for separated atoms. The inner electrons bound closely to the nucleus participate with a rather small probability in the exchange processes. Analogously to the valence electrons of the atoms there is the valence band in solid bodies. Its population by electrons defines essentially the properties of the solid body. If the valence band is not completely occupied it will be responsible for the conductivity of electrons. A valence band not completely occupied

is called **conduction band**.

If it is completely occupied the next not completely occupied band will be called conduction band.

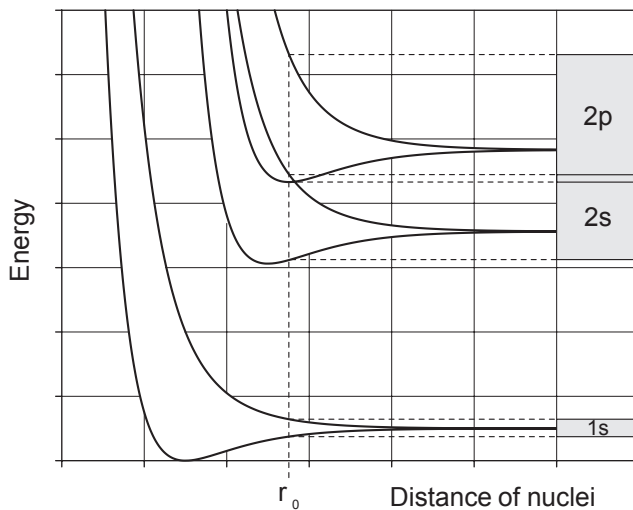


Fig. 3: Band formation by several electrons. The most outside electrons are responsible for the equilibrium distance r_0 .

In the following section the question is to be answered how the density of states of a band of electrons looks like and on which quantities it depends. Before doing that and for reasons of completeness another attempt is made to determine the electron distribution within a solid body.

1.3 Periodic potentials

Although quantum mechanics is fairly powerful, up to now one has not succeeded to calculate the energy eigenvalues of complex atoms and molecules. One generally relies on skilful statements for the energy potentials to which the electrons are submitted. The statement of periodical potentials has been found to be especially powerful.

1.4 Fermi distribution

In Fig. 3 we have shown that the energy bands are the result of the mutual interaction of the atoms. Each band has a particular width ΔE , the magnitude of which is determined by the exchange energy and not by the number N of the interacting atoms. Furthermore we know that the number of energy levels within a band is determined by the number of interacting electrons. The Pauli principle states that such a level can only be occupied by two electrons. In this case the spins of the electrons are antiparallel. Within a band the electrons are free to move and they have a kinetic energy of

$$E = \frac{1}{2}mv^2 \quad \text{or} \quad E = \frac{p^2}{2m}$$

The mass of the electron is m , v the velocity and p the impulse. The constant potential energy will not be taken into consideration. Furthermore we will set the energy of the lower band edge to zero. The maximum energy $E_{\max}$ of an electron within a band can not pass the value ΔE since otherwise the electron would leave the band and no longer be a part of it. Consequently we can write:

$$E_{\max} = \Delta E = \frac{1}{2m} p_{\max}^2$$

We still have to find out how many electrons of energy $E \leq E_{\max}$ exist and within a second step we wish to know how

many electrons exist in the energy interval dE . To reach this goal we will use a trick already applied in deriving the number of modes in a cavity resonator. Here we will consider electrons instead of photons. The course of considerations will be the same since we can attribute to each electron a wave with wave vector $\vec{k}$. For the impulse $\vec{p}$ we write:

$$\vec{p} = \hbar \cdot \vec{k}$$

Only such electron energies are permitted within a volume the wave functions of which are zero at the walls. To express it in a more simple way: an integer multiple of half the wavelength λ of the associated standing wave must fit, for instance, into the length L of a cube:

$$L_x = n_x \frac{\lambda}{2} \quad \text{and} \quad k_x = \frac{2\pi}{\lambda}$$

For the electron energy of the cube we get:

$$E = \frac{p^2}{2m} = \frac{\hbar^2}{2m} \vec{k} \cdot \vec{k} = \frac{\hbar^2}{2m} (k_x^2 + k_y^2 + k_z^2)$$

$$E = \frac{2\hbar^2}{m} \left(\frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} + \frac{n_z^2}{L_z^2} \right) = \frac{2\hbar^2}{mL^2} (n_x^2 + n_y^2 + n_z^2)$$

Let's remember the equation of a sphere

$$R^2 = x^2 + y^2 + z^2$$

and compare it with the equation for E . We recognise an analogous equation of the following type:

$$E \frac{mL^2}{2\hbar^2} = (n_x^2 + n_y^2 + n_z^2)$$

$$E = \frac{\hbar^2 k^2}{2m} \quad \text{or with}$$

$$L^2 \frac{k^2}{\pi^2} = n_x^2 + n_y^2 + n_z^2$$

The radius of this sphere is Lk/π and n_1, n_2, n_3 are the x, y, z coordinates. As n is an integer and positive they only generate one eighth of a complete sphere set up by a spatial lattice with lattice constant 1.

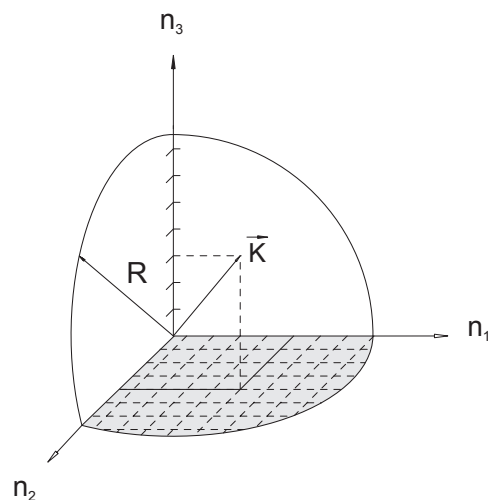


Fig. 4: Calculation of the electron density

Permissible are only such wave vectors $\vec{k}$, the components of which are coinciding with the n values or, to express it

differently, each point of intersection of the lattice represents a valid solution for the wave vector k of a stationary wave. The answer to the initially raised question regarding the number of electrons for a particular length L of a potential box results now out of the counting of the number of points of intersection (Fig. 4).

This work can also be done analytically. If one uses the formula for the volume of a sphere $V_{\text{sphere}} = \frac{4}{3} \pi R^3$ one gets for one eighth of a sphere with a radius for an upper limit of energy at E_{max} :

$$N(E_{\text{max}}) = \frac{1}{8} \cdot \frac{4}{3} \pi \cdot \left(L \frac{k}{\pi} \right)^3$$

with $E = \frac{\hbar^2 k^2}{2m}$ or $k^2 = \frac{4\pi^2}{h^2} 2mE$ one gets:

$$N(E) = \frac{8}{3} \frac{\pi}{h^3} V \cdot (2mE)^{3/2}$$

Here V is the volume of the box. An additional factor of 2 accounts for the fact that two electrons are admitted in each state if their spins are antiparallel. Let's divide $N(E)$ by the volume V to get the electron density

$$n(E) = \frac{8}{3} \frac{\pi}{h^3} \cdot (2mE)^{3/2}$$

The electron density per unit energy $dn(E)/dE$ is found by differentiation:

$$dn(E) = \frac{4\pi}{h^3} (2m)^{3/2} \sqrt{E} \cdot dE$$

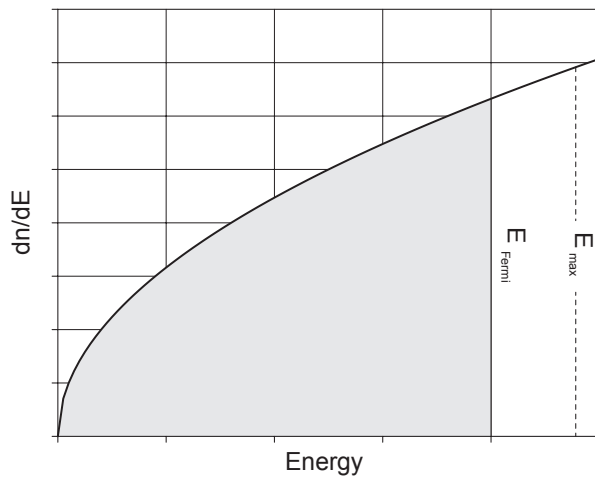


Fig. 5: Number of electrons per unit volume V and energy interval dE as a function of the energy E .

The situation in Fig. 5 shows that the band has not been completely filled up since the Fermi energy is smaller than the maximal possible energy. This means that this band is a conduction band. If the Fermi energy would be equal to the maximal energy we would have a valence band. A transfer of this knowledge to the energy level scheme of Fig. 3 and a selection of the 2s band would provide the picture of Fig. 6. Up to this point we anticipated that the temperature of the solid body would be 0 K. For temperatures deviating from this temperature we still have to respect thermodynamic aspects namely additional energy because of heat introduced from outside. Fermi and Dirac described this situation using statistical methods. The electrons were treated as par-

ticles of a gas: equal and indistinguishable. Furthermore it was presumed that the particles obey the exclusiveness principle which means that any two particles cannot be in the same dynamic state and that the wave function of the whole system is antisymmetrical.

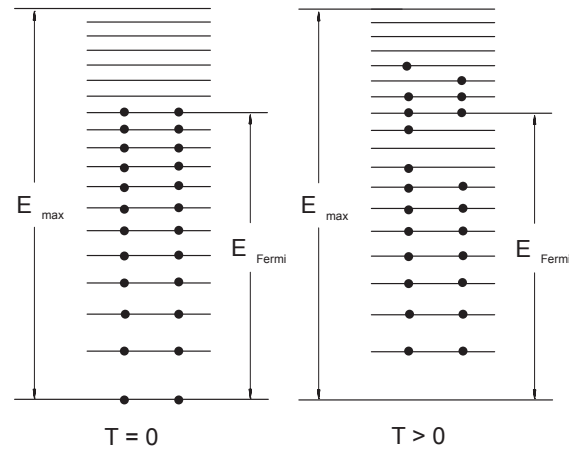


Fig. 6: Distribution of free electrons over the energy states within a conduction band

Particles which satisfy these requirements are also called Fermions. Correspondingly all particles which have a spin of $1/2$ are Fermions and obey the Fermi Dirac statistics. Electrons are such particles. Under respect of these assumptions both physicists got the following equation for the particle density of the electrons within an energy interval dE :

$$\frac{dn(E)}{dE} = \frac{4\pi}{h^3} (2m)^{3/2} \cdot \frac{\sqrt{E}}{e^{\frac{E-E_{\text{Fermi}}}{kT}} + 1} \cdot dE$$

The above equation is illustrated by Fig. 7.

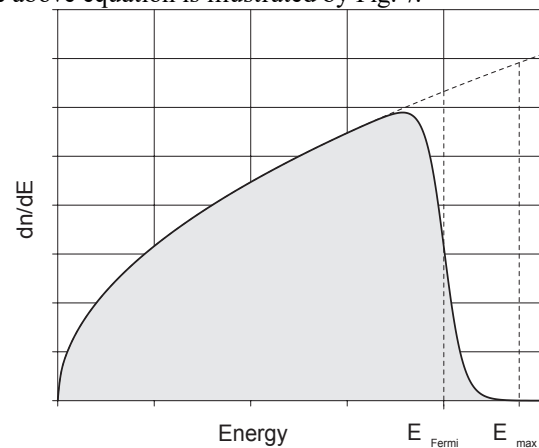


Fig. 7: Number of electrons per unit volume and energy interval dE as a function of the energy E , but for a temperature $T > 0$.

As shown in Fig. 6 by introduction of thermal energy the „highest“ electrons can populate the states which are above them. Based on these facts we are well equipped to understand the behaviour of solid bodies. We are going to concentrate now our special interest on the semiconductors which will be presented in the next chapter with the help of the previously performed considerations.

1.5 Semiconductors

Prior to discussing the semiconductor's role as a 'lasing' medium, it is crucial to understand the idea of 'holes.'

These are states within a band that lack electrons and are thus called 'holes.' Whenever an electron leaves a state, it creates a hole, and when an electron occupies a new state, it removes a hole. This process can be viewed as the hole and electron exchanging their positions (Fig. 7). Holes have their own dynamic behaviors and can be treated as particles similar to electrons. Importantly, holes have properties that are exactly opposite to those of electrons. Since holes move along the same path as electrons, they have the same mass, except the hole's mass has an opposite sign. Moreover, holes carry a positive charge.

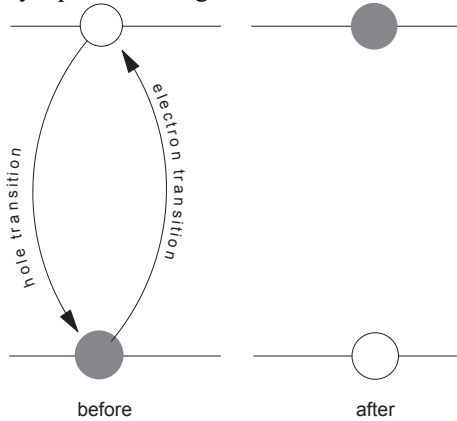


Fig. 8: Electron and hole transition

Once the existence of the holes has been accepted they also have to have a population density. It will be introduced in the following. For this reason we complete Fig. 6 as shown in Fig. 9.

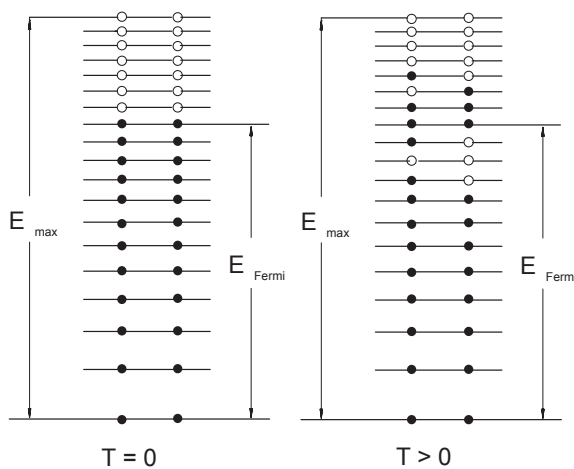


Fig. 9: Distribution of the holes and the electrons within an energy band

It is easy to understand that on one side the holes are preferably at the upper band edge and on the other side their population density results out of the difference of the population density minus the population density of the electrons. Fig. 10 shows the population density of the electrons. Fig. 11 shows the difference and in so far the population density of the holes. Attention has to be paid to the fact that the abscissa represents the energy scale of the band and not the energy of the holes.

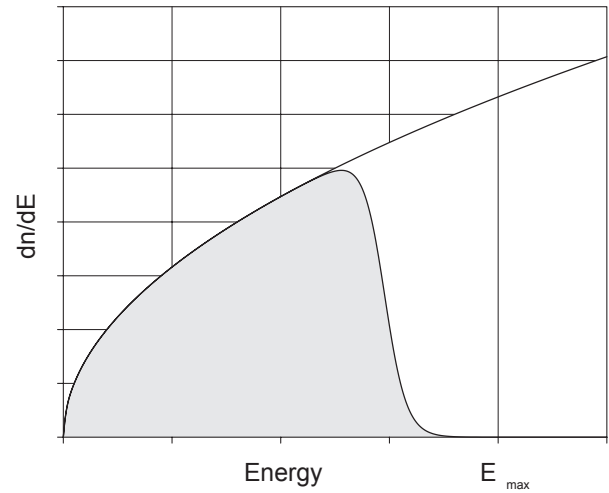


Fig. 10: Population density of the electrons

To prepare the discussion of optical transitions in semiconductors it gives a sense to modify the diagrams. Until now the abscissa was used as energy scale for the diagrams of the state and population densities. For the presentation of optical transitions it is more practical to use the ordinate as energy scale. To get use to it Fig. 10 has been represented in the modified way in Fig. 12. The shown population density refers to an energy scale for which the lower edge of the valence band has been set arbitrarily to zero. The represented situation refers to a semiconductor where the distance between conduction and valence band is in the order of magnitude of thermal energy (kT). Here the Fermi energy lies in the forbidden zone.

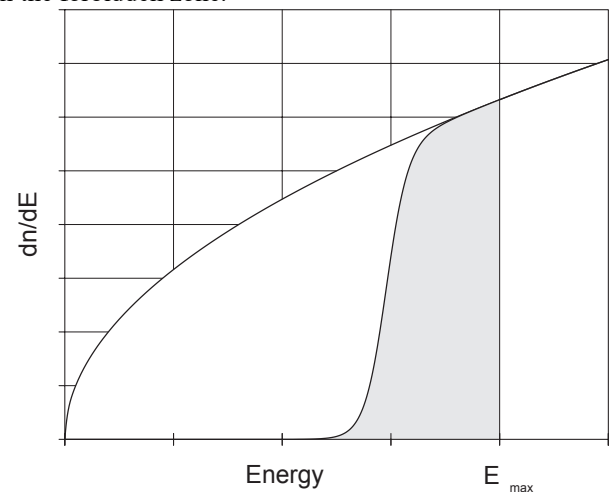


Fig. 11: Population density of the holes

Because of the thermal energy some electrons have left the valence band and created holes. For the following considerations it is sufficient to learn something about the population densities of the electrons in the conduction band as well as about the holes in the valence band. As will be shown later there are optical transitions from the conduction band to the valence band provided they are allowed. Near the lower band edge of the conduction band the state densities are admitted to be parabolic. The same applies to the holes located at the upper boundary of the valFig. 13nd (Fig. 13). The densities of states provide information about the quantity of states available for occupation, while the spectral distribution reveals how electrons and holes are spread across these states. Near the band edges, the spectral distribution corresponds to a Boltzmann distribution.

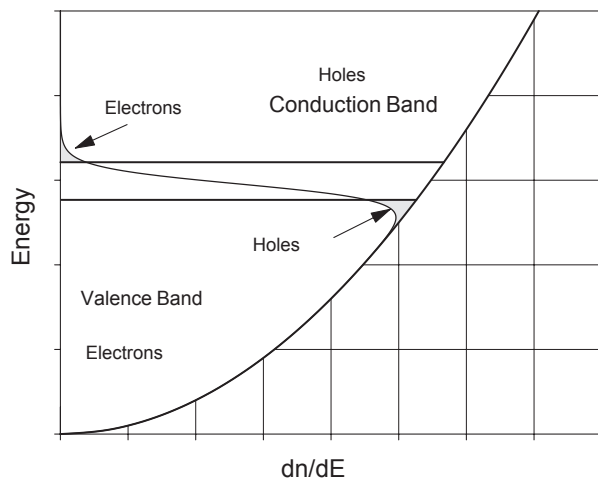


Fig. 12: Population density on the energy scale

If we succeed to populate the conduction band with electrons and to have a valence band which is not completely occupied by electrons (Fig. 13) electrons may pass from the conduction band to the valence band. That way a photon is generated. By absorption of a photon the inverse process is also possible.

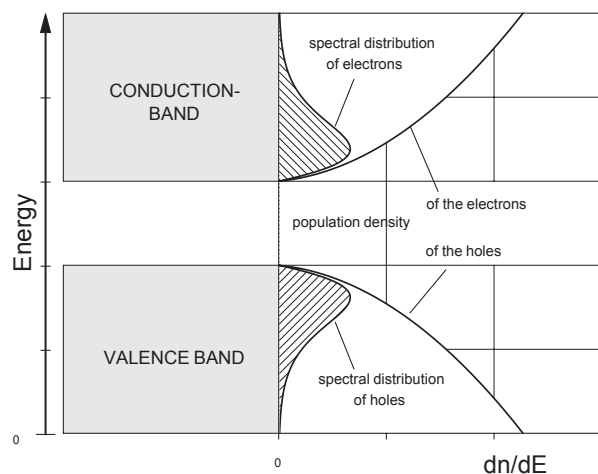


Fig. 13: Densities of states and spectral distributions

The following illustration Fig. 14 shows the situation of a population inversion in a semiconductor. Attention must be drawn to the fact that, until now, we only discussed a semiconductor consisting of one type of atoms. Consequently the situation shown in Fig. 14 is, at least for this type of direct semiconductor, only fictitious. It can only be created for very short intervals of time and can therefore not be taken into consideration for the realisation of a semiconductor laser. By doping the basic semiconductor material we can create band structures with different properties.

A very simple example may be the semiconductor diode where the basic material, germanium or silicon, is converted into p or n conducting material using suitable donors and acceptors. By the connection of the doped materials a barrier (also called active zone) is formed. It will be responsible for the properties of the element. Silicon is mainly used for highly integrated electronic circuits while ZnS is chosen as fluorescent semiconductor for TV screens.

As light emitting diodes and laser diodes so called mixed

semiconductors like AlGaAs are in use. Mixed semiconductors can be obtained whenever within the semiconductors of valence three or five individual atoms are replaced by others of the same group of the periodical system. The most important mixed semiconductor is aluminum gallium arsenide (AlGaAs), where a portion of the gallium atoms has been replaced by aluminum atoms. This type of semiconductor can only be produced by a fall out as thin crystal layer, the so called epitaxy layer, on host crystals. To perform this stressfree it is important that the lattice structure of the host crystal (lattice matching) coincides fairly well with the lattices structure of AlGaAs.

This is the case for GaAs substrate crystals of any concentration regarding the Al and Ga atoms within the epitaxy layer. In that way the combination of AlGaAs epitaxy layers and GaAs substrates offers an ideal possibility to influence the position of the band edges and the properties of the transitions by variation of the portions of Ga or Al.

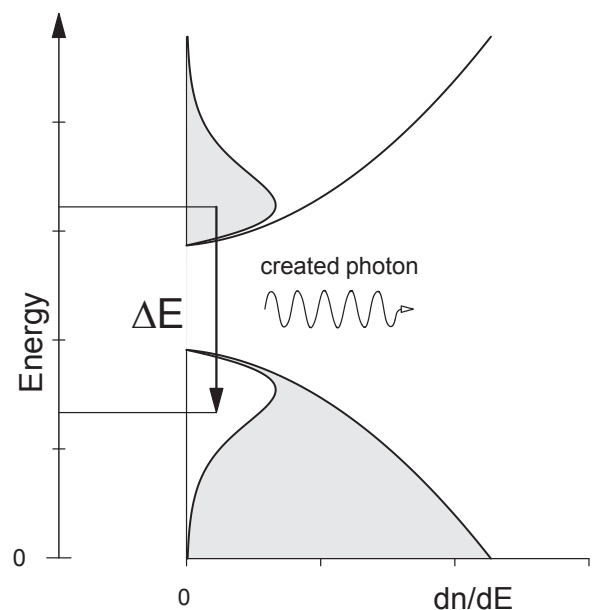


Fig. 14: Population inversion in a semiconductor for $T > 0$

1.6 Semiconductor laser

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.

- | | | |
|----|--------------|------------------|
| 1. | R. N. Hall | General Electric |
| 2. | M. I. Nathan | IBM |
| 3. | T. M. Quist | MIT |

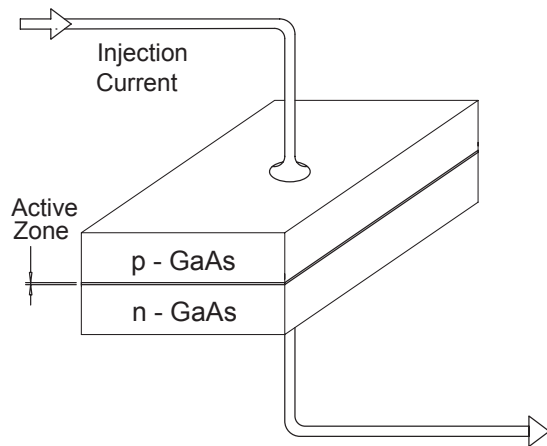


Fig. 15: Simple laser diode around 1962, working at 70 K and with 100 kA/cm² in the pulse mode.

The first laser was basically made of highly doped GaAs (Fig. 15). 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. In the course of the following years the threshold could be lowered to 60 kA/cm² by improving the crystals but only the use of a hetero-transition (Bell Labs. and RCA-Labs.) brought the „break-through“ in 1968. The threshold could be lowered to 8 kA/cm² and working in the pulse mode at room temperature was possible (Fig. 16).

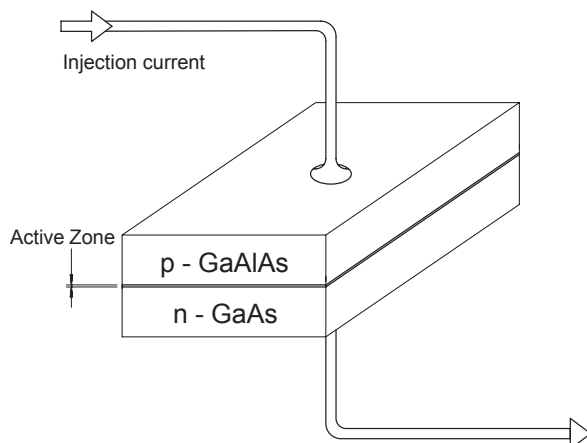


Fig. 16: Simple-heterostructured laser around 1968, working at 8 kA/cm² in pulse mode at room temperature.

In this concept a layer of p conducting GaAlAs is brought on the p layer of the pn transition of GaAs. The slightly higher band gap of GaAlAs compared to GaAs ensures that a potential barrier is created between both materials in a way that charge carriers accumulate here and the formation of inversion is increased respectively the laser threshold is remarkably lowered to 8 kA/cm².

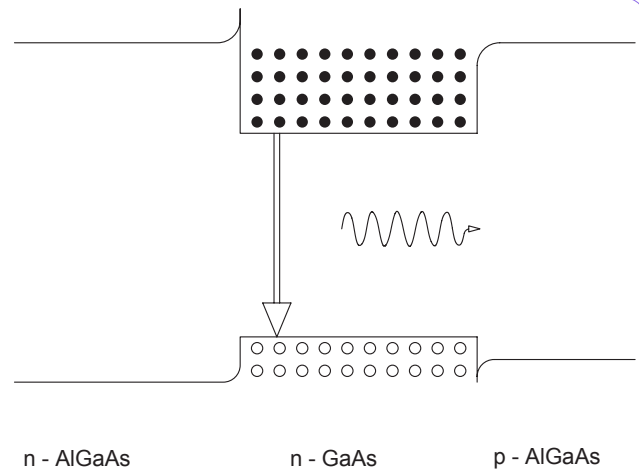


Fig. 17: Energy band diagram of a N n P - double hetero structure.

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 (Fig. 18 and Fig. 19).

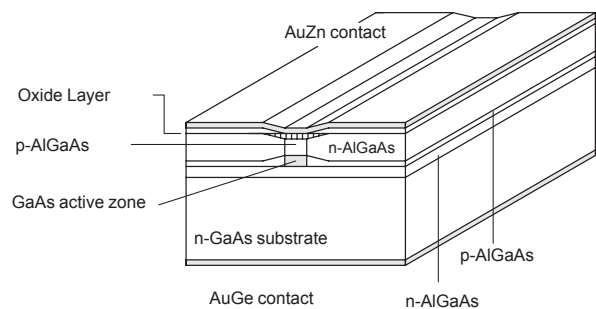


Fig. 18: „Buried“ hetero structure. The active zone has been buried between some layers which ensure an optimal beam guidance in the zone.

1.7 Resonator and beam guidance

As already mentioned at the beginning the diode laser differs from the „classical“ lasers in the dimensions of the resonator and in the propagation of the beam. For the diode lasers the active material represents the resonator at the same time. Furthermore the ratio of the resonator length (300 μm) to the wavelength (820 nm) is:

$$L / \lambda = 366 ,$$

For a HeNe-Laser ($\lambda = 632 \text{ nm}$) with a typical resonator length of 20 cm this ratio is 3 108. Considering additionally the lateral dimensions of the resonator we get a ratio of 12.5 for the diode lasers with a typical width of 10 μm for the active zone. With capillary diameters of the He-Ne tubes of about 1 mm one gets a value of 1582. This already indicates that the beam characteristics of the laser diode will distinguish significantly from „classical“ lasers.

1.8 Divergence and intensity distribution

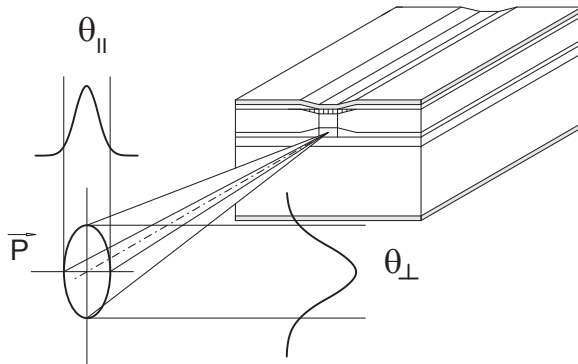


Fig. 19: Elliptical beam profile of a diffraction limited laser diode in the far field (some meters).

Not only the beam guidance but also the size of the laser mirrors influences the beam geometry. Generally for conventional lasers the mirrors are very large compared with the beam diameter. The laser mirror (crystal gap area of the active zone) of the laser diodes has a size of about $10\ \mu\text{m} \times 2\ \mu\text{m}$, through which the laser beam has „to squeeze“ itself. Diffraction effects will be the consequence and lead to elliptical beam profiles (Fig. 19).

The polarisation is parallel to the "junction plane", that is the plane which is passed by the injection current perpendicularly. The divergence angles $\theta_{\perp}$ and $\theta_{||}$ differ by about $10\text{-}30^\circ$ 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 (Fig. 20). It amounts to about $10\ \mu\text{m}$ 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 $2\text{-}3\ \mu\text{m}$ width).

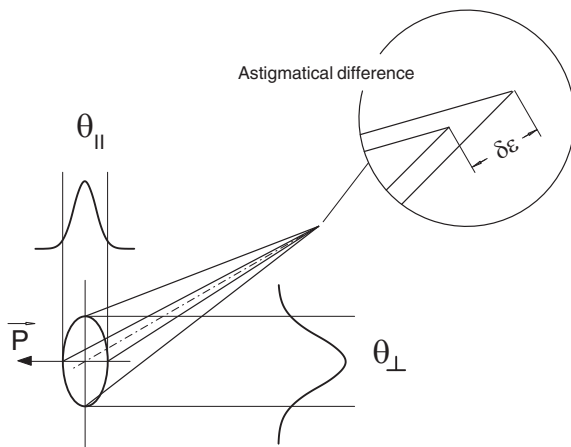


Fig. 20: Astigmatic difference $\delta\epsilon$

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 „civilised“ diode lasers. For the time being they are only available for powers up to 200 mW. High power diode lasers as used, for example, to pump Nd YAG lasers partially have very fissured nearly rectangular intensity profiles.

1.9 Polarisation

It is understandable that the laser radiation of the diodes has a distinct direction of polarisation, since the height of the exit window is 4 times and the width 12.5 times larger than the wavelength.

Because of the fraction of spontaneous emission the light of the laser diode also contains components oscillating in the vertical direction

The ratio of polarisation, $P_{\perp}$ to $P_{||}$, depends on the output power since for higher laser power the ratio of spontaneous to stimulated emission is changing (Fig. 22).

1.10 Spectral properties

Another property of the diode laser is the dependence of its wavelength on the temperature (about $0.25\ \text{nm}/^\circ\text{K}$) and on the injection current (about $0.05\ \text{nm}/\text{mA}$).

Users who need a well defined wavelength have to adjust temperature and injection current in a way that the wavelength remains constant. By changing the temperature the wavelength of the laser radiation can be altered.

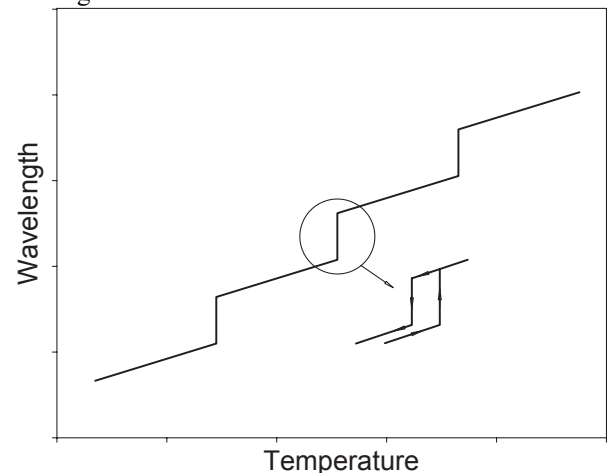


Fig. 21: Emission wavelength as a function of the crystal temperature of the laser diode and hysteresis.

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 favourable conditions will start to oscillate. As the distance between two successive modes

is very large for the extremely short resonator (typical $300 \mu\text{m}$), 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 jump-free range of the characteristic line (Fig. 21).

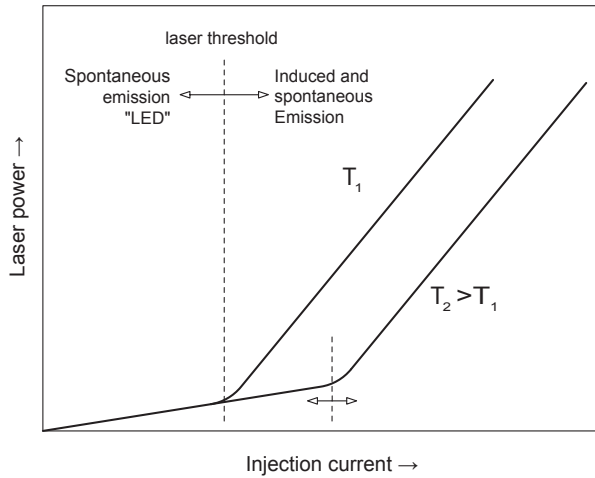


Fig. 22: Laser power versus injection current with the temperature T as parameter

A similar behaviour 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 (Fig. 40). The wavelength of the laser diode depends on the temperature T and the injection current I in the following way:

$$\begin{aligned}\lambda(T, I) = & \lambda(T_0, I_0) + \alpha_T(T - T_0) + \alpha_I(I - I_0) \\ & + \alpha_T^2(T - T_0)^2 + \alpha_I^2(I - I_0)^2 + \dots \\ & + \alpha_T^n(T - T_0)^n + \alpha_I^n(I - I_0)^n\end{aligned}$$

$\lambda(T_0, I_0)$ is a known wavelength at T_0 and I_0 .

Generally it is sufficient to consider only the linear terms. For a precision of $\delta\lambda/\lambda < 10^{-6}$ the quadratic terms have to be respected. The equation is valid within a jump-free range. The requirement $\lambda(T, I) = \text{const.} = \lambda_c$ provides directly:

$$I = \frac{(\lambda_c - \lambda_0)}{\alpha_I} - \frac{\alpha_T}{\alpha_I}(T - T_0)$$

One gets a dependence as shown in Fig. 23

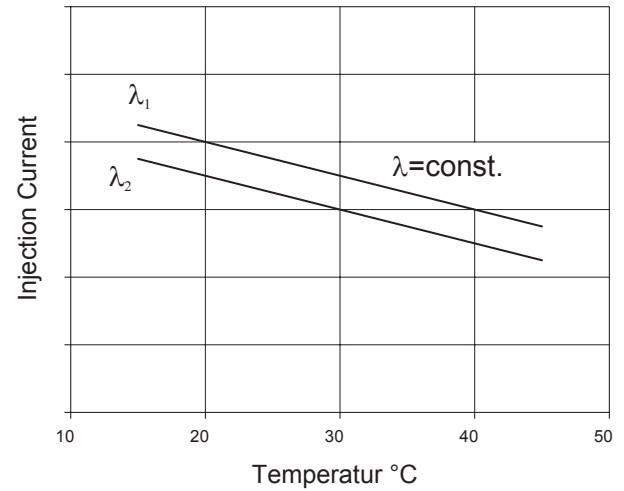


Fig. 23: Injection current as a function of the temperature for constant wavelength

1.11 Optical power

In regard to „classical“ lasers the light of a diode laser contains a remarkable high fraction of non-coherent „LED“ radiation. For currents underneath the laser threshold the spontaneous emission is dominant. Stimulated emission is responsible for the strong increase above the laser threshold. The threshold current can be determined by the point of intersection of the extrapolated characteristic lines of the initial and of the lasing working mode. The rounding off of the characteristic line is the result of spontaneous emission. It also is the cause for the oscillation of several modes next to the threshold. At higher currents the mode spectrum becomes more and more clean.

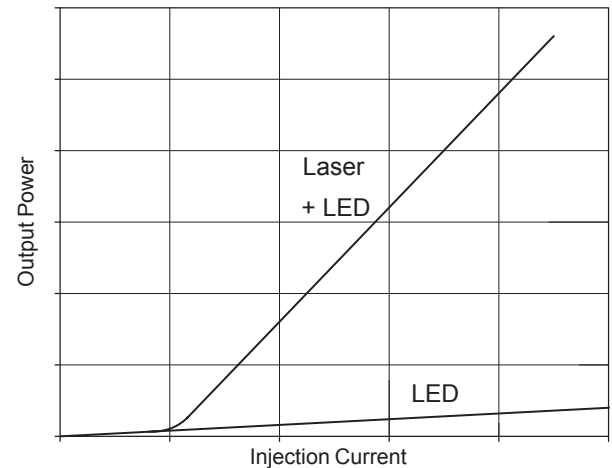


Fig. 24: Output power of the laser diode as a function of the injection current

2.0 Detectors, properties

Semiconductor pn-transitions with a band gap of E_g are suitable for the detection of optical radiation if the energy E_p of the photons is equal or greater than the band gap.

$$E_p = \hbar\omega \geq E_g$$

In this case an arriving photon can stimulate an electron to pass from the valence band to the conduction band. (Fig. 25).

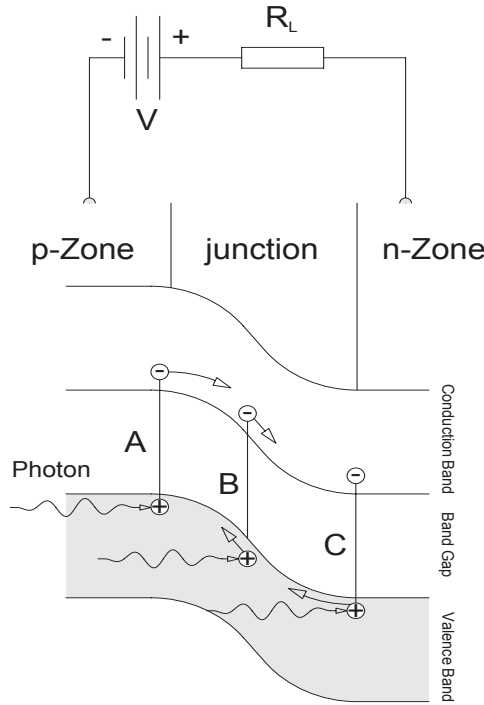


Fig. 25: Absorption of a photon with subsequent transition of the stimulated electron from the valence band to the conduction band

Here three types of events are possible:

- A.** An electron of the valence band in the p-zone is stimulated and enters the p-zone of the conduction band. Because of the external electric field due to the voltage V it will diffuse through the barrier layer into the n-zone and contributes to the external current passing the resistor R_L unless it recombines in the p-zone.
- B.** If an electron of the barrier layer is hit by a photon the hole of the barrier layer will migrate into the p-zone and the electron into the n-zone. The drift of both charges through the barrier layer causes a current impulse. The duration of the impulse depends on the drift speed and on the length of the barrier layer.
- C.** The case is similar to case A. The hole migrates due to the presence of the external field into the p-zone or recombines in the n-zone.

Only electrons which are in the barrier layer (case B) or near the boundary of the barrier layer (area of diffusion, case A and C) contribute to the external current due to stimulation by photons. All others will recombine within their area. In the utmost case one elementary charge q can be created for each incoming photon. As already mentioned, not every photon will create in the average a current impulse. In this context the production rate G , leading to an average current $\langle i_{ph} \rangle$ is defined as follows:

$$\langle i_{ph} \rangle = q \cdot G$$

At a light energy of P_0 a number of $\frac{P_0}{\hbar\omega}$ photons will hit the

detector as $\hbar\omega$ is just the energy of one photon. But only that fraction of photons is converted into current pulses which is absorbed in the barrier layer. This fraction may

be called $\eta \cdot P_0$, where η is called quantum efficiency. The number of generated current pulses or the production rate

will be

$$G = \frac{\eta}{\hbar\omega} \cdot P_0$$

and the average photo current:

$$\langle i_{ph} \rangle = \frac{\eta \cdot q}{\hbar\omega} \cdot P_0$$

Because of processes which are typical for semiconductors there is already a current flowing even if there are no photons entering the detector. This current is called „dark“ current and has four reasons:

1. Diffusion current, it is created because of statistical oscillations of the charge carriers within the diffusion area
2. Regeneration or recombination current, it is generated by random generation and annihilation of holes
3. Surface currents, which are hardly avoidable since the ideal insulator does not exist
4. Avalanche currents are flows of electrons which appear at high electric field strengths, if, for example, a high voltage is applied to the photodiode

All these effects contribute to the dark current i_D in a way that finally the characteristic curve of the diode can be expressed as follows:

$$i = i_s \left(e^{\frac{q \cdot U_D}{kT}} - 1 \right) - \langle i_{ph} \rangle = i_D - \langle i_{ph} \rangle$$

This current i passes the load resistor R_L and provokes the voltage drop U_a , which represents the signal.

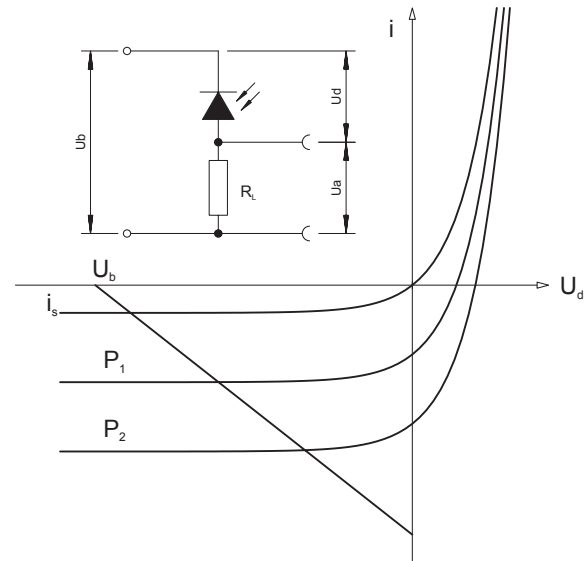


Fig. 26: Characteristic line of a photodiode in the photoconductive mode

$$i = i_s \left(e^{\frac{q \cdot U_d}{kT}} - 1 \right) - \langle i_{ph} \rangle = \frac{U_a}{R_L}$$

A good detector of optical communication technology is

characterised by the fact that it is very fast (up to the GHz range) and that it has a high quantum efficiency which means that it is very sensitive. Depending on the wavelength range which has to be covered by the detector one uses silicon or germanium semiconductor material for the construction of the detectors.

2.1 Ge and Si PIN-diodes

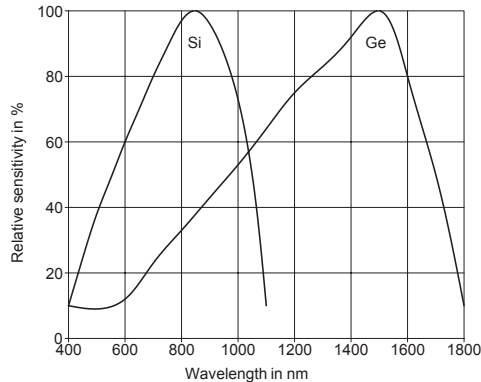


Fig. 27: Relative sensibility for Si und Ge photo detectors

To have absorption of a photon at all its energy has to fit into the band structure of the material under consideration. From the condition

$$E_{ph} = \hbar\omega = h\nu = \frac{hc}{\lambda} \geq E_G$$

one recognises that for large wavelengths the energy of the photon may no more be sufficient „to lift“ the electron in a way that it passes the band gap. For smaller wavelengths one has to respect that the conduction band and also the valence band have upper edges which is followed by a band gap. Photon energies which pass the upper limit of the conduction band can no more be absorbed. The wavelength of the applied light source decides which detector material is to be used. For wavelengths above 1 μm up to 1.5 μm Germanium is recommended. Underneath these values Silicon detectors are used. In the present experiment a laser diode of 810 nm wavelength is applied. Therefore a silicon detector is used. To get a high quantum efficiency not a PN but a PIN detector has been chosen.

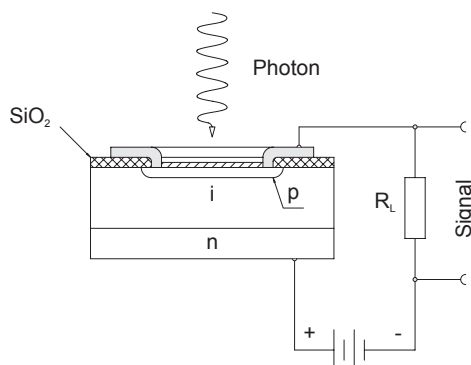


Fig. 28: Design of a PIN detector

Contrary to a detector with a simple pn-layer this type of detector has an intrinsic conducting layer inserted in between the p-and n-layer. Therefore the name PIN-diode. The reason for this is to enlarge the barrier layer which increases the probability of absorption of a photon and the generation of a current impulse, e.g. the quantum efficiency. The quantum efficiency for such an arrangement is:

$$\eta = (1 - R)(1 - e^{-\alpha d})e^{-\alpha d_p}$$

R is the Fresnel reflection at the Si or Ge surface which is hit by the photons, α is the coefficient of absorption, d the thickness of the intrinsic zone and d_p the thickness of the p-layer. By attachment of a reflex reducing layer on the upper side of the p-layer R can get a value of less than 1%. Since αd_p is anyhow $\ll 1$, the thickness of the intrinsic layer should be chosen as large as possible. The consequence of this is that the drift time rises and the limiting frequency of the detector is reduced. In so far a compromise between high quantum efficiency and high limiting frequency has to be made. In this experiment a PIN-Si-photo diode, type BPX61 is used. It has the following characteristic values:

Quantum efficiency η at 850 nm	90 %
Rise time $T_r = 2.2 R_L C_j$ 10%-90% at $R_L = 50\Omega$ and $U_d = 10V$	1.7 ns
Capacity C_j at $U_d =$	
0 V	73 pF
1 V	38 pF
10 V	15 pF
dark current i_d at $U_d = 10V$	2 nA
Photosensitivity at $U_d = 5V$	70 nA/lx

3.0 Description of Components

3.1 The full Set-Up

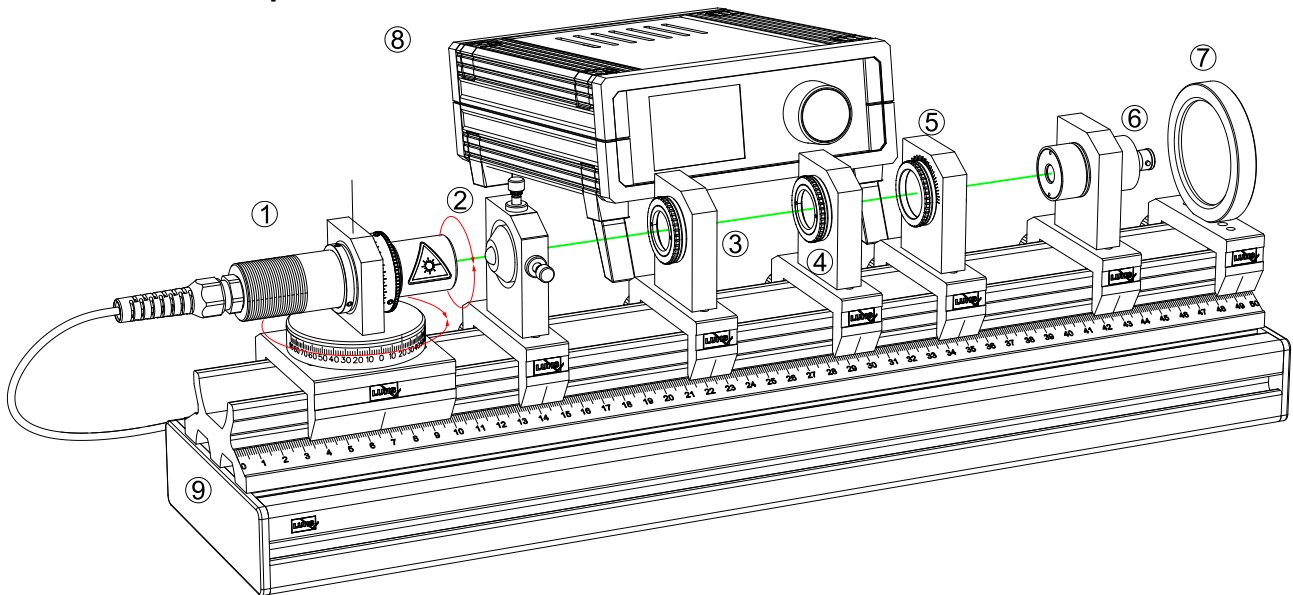


Fig. 29: The figure shown above displays all the required modules

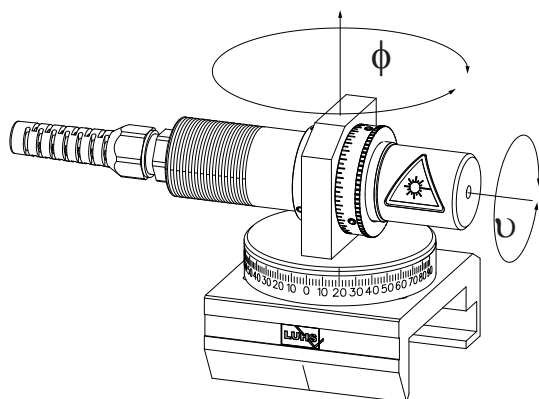
The following measurements and experiments can be performed using the setup shown in Fig. 29:

- Laser diode output power as a function of injection current and temperature (page 20).
- Measurement of the spatial beam profile of the laser diode (page 20).
- Measurement of the wavelength as a function of the injection current and the temperature of the laser diode (using an optional spectrometer) (page 21).
- Measurement of the polarization of the laser diode (page 22).
- Adjustment of the beam profile to a circular profile using cylindrical lenses (page 23).

The following modules are presented on the following pages:

- “Module 1 Diodelaser” on page 14
- “Module 2 Collimating Optics” on page 15
- “Galilean cylinder lens telescope (Module 3 and 4)” on page 15
- “Module 5 Polarisation Analyser” on page 15
- “Module 6 Photodiode” on page 15
- “Module 7 Translucent screen” on page 16
- “Module 8 Digital Diode Laser Controller MK1” on page 16
- “Module 9 Rail and Carrier” on page 18

3.2 Module 1 Diodelaser

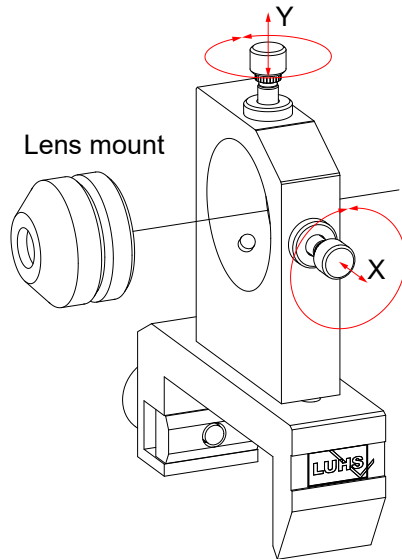


A laser diode producing 10 mW of power at a wavelength of 515 nm is securely mounted onto a Peltier cooler to maintain stable operating temperatures. The temperature of the laser diode is accurately measured by means of an integrated thermistor embedded within the assembly. The

laser head itself is fixed in a mounting plate attached to a carrier, designed so that it can be precisely rotated around the laser axis (v) as well as adjusted vertically relative to the axis (ϕ). This device can emit highly concentrated invisible light which can be hazardous to the human eye. The operators of the diode laser module must follow the safety precautions found in IEC 60825-1 “Safety of laser products Part 1: Equipment classification, requirements and user’s guide” when connected to the controller and powered up. The diode laser is connected via a 15 pin SubD HD connector (CN) to the controller MK1. Inside the connector an EPROM contains the data of the laser diode and when connected to the controller, these data are read and displayed by the controller

3.3 Module 2 Collimating Optics

A high precision aspheric glass lens is mounted into a lens holder.



The lens mount is aligned using three pins with ball tips. One pin is spring-loaded, while the other two can be adjusted along the X and Y axes.

3.4 Galilean cylinder lens telescope (Module 3 and 4)

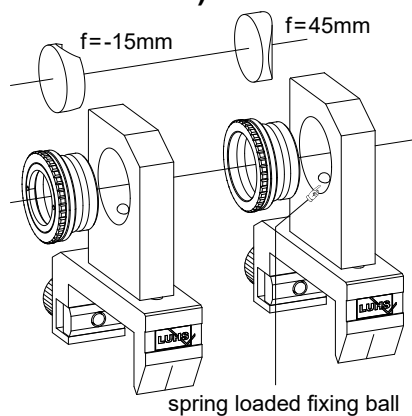


Fig. 30: Beam expander with cylindrical lenses

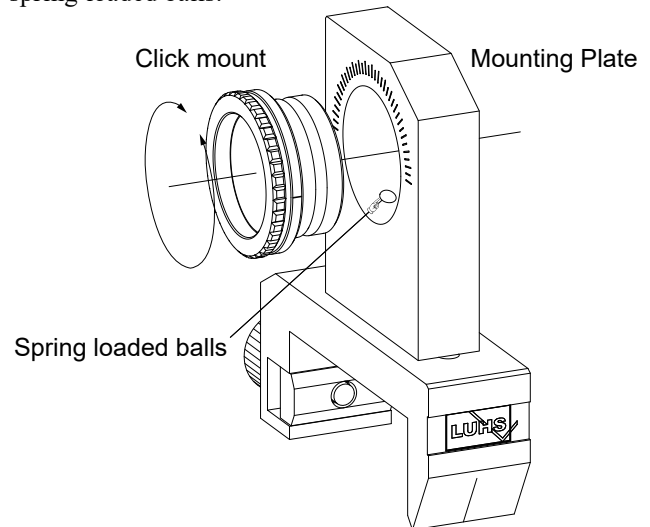
For best efficiency of optical pumping, it makes sense to form the laser beam of the diode laser such, that a circular beam results. This is accomplished by a beam expander with cylindrical lenses which affects only one direction of the laser diode's beam. To maintain the rotation, the first lens is made adjustable. Both lenses can be rotated in their holders to adjust the roundest spot size.

Such a telescope is made up from two cylindrical lenses and acts a beam expander, however, it effects only on one direction of the passing beam. It allows to convert an elliptical beam into an almost round one. The expansion ratio is 3 x. The first lens f_1 is a concave and the second one f_2 a convex cylindrical lens. The lens f_1 is mounted into an XY adjustment holder to position the processed beam into the desired direction. The second lens is mounted into a C25 click holder which is kept in position by three spring loaded balls (SB) snapping into the groove CG of the C25 mount.

3.5 Module 5 Polarisation Analyser

A click mount contains a polarizing film that functions as

a polarization analyzer. The mount is inserted into the mounting plate, where it can rotate. It is held in place by spring-loaded balls.



3.6 Module 6 Photodiode

A Si PIN photodiode is integrated into a 25 mm housing with two click grooves (PD). A BNC cable and connector is attached to connect the module to the MK1 diode laser controller. The photodetector module is placed into the mounting plate (MP) where it is kept in position by three spring loaded steel balls.

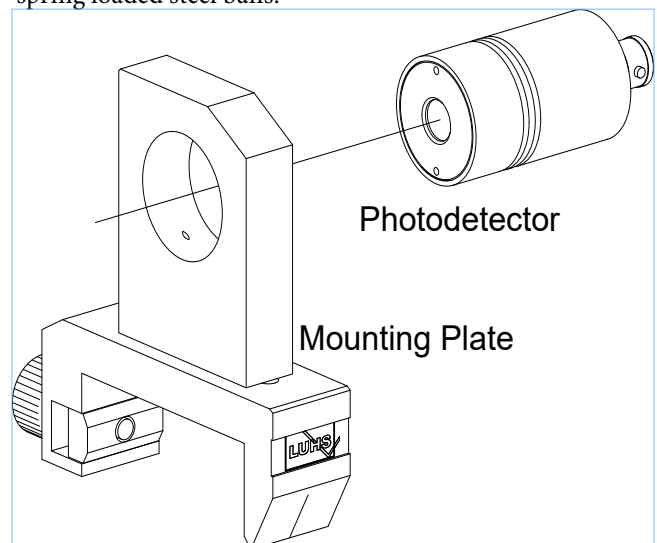


Fig. 31: Photodetector module

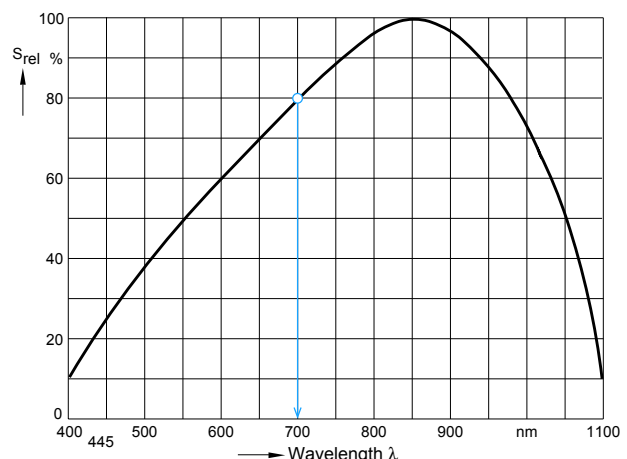


Fig. 32: Sensitivity curve of the BPX61 photodiode

Parameter	symbol	value
Rise and fall time of the photo current at: $R_L=50\ \Omega$, $V_R=5V$, $\lambda=850\text{ nm}$ and $I_p=800\ \mu A$	t_r, t_f	20 ns
Forward voltage $I_F = 100\text{ mA}$, $E = 0$	V_F	1.3 V
Capacitance at $V_R = 0$, $f = 1\text{ MHz}$	C_0	72 pF
Wavelength of max. sensitivity	λ_{Smax}	850 nm
Spectral sensitivity $S \sim 10\%$ of S_{max}	λ	1100
Dimensions of radiant sensitive area	$L \times W$	7 mm ²
Dark current, $V_R = 10\text{ V}$	I_R	$\leq 30\text{ nA}$
Spectral sensitivity, $\lambda = 850\text{ nm}$	$S(\lambda)$	0.62 A/W

Table 1: Basic parameters of Si PIN photodiode BPX61

The Mk2 controller contains a digital resistor and provides +12 VDC for the reverse voltage of the photodiode. They are connected to the BNC input (PDIN) as shown in the schematic of Fig. 33. At the output PDOUT of the signal box a signal is present which is given by the following equation:

$$I_c = \frac{U_c}{R_s} = \frac{U_{display}}{R_s \cdot \text{Gain}}$$

I_c is the photo current created by illuminating the photodiode with light. U_c is the voltage drop across the selected load resistor R_s . $U_{display}$ is the value of U_c displayed on the controller's touch screen multiplied by the selected gain (GAIN). To convert the measured voltage U_c into a respective optical power we use of the spectral sensitivity $S(\lambda)$ [A/W], which depends on the wavelength of the incident light according to Fig. 32. From the Table 1 we take the value for $S(850\text{ nm})$ as 0.62 A/W. To obtain the value for another wavelength, 445 nm for instance, we have to multiply this value with the $S_{rel}(445\text{ nm})$ from Fig. 32 (23% or 0.23).

The detected optical power P_{opt} in W is given as:

$$P_{opt} = \frac{I_c}{S(\lambda)}$$

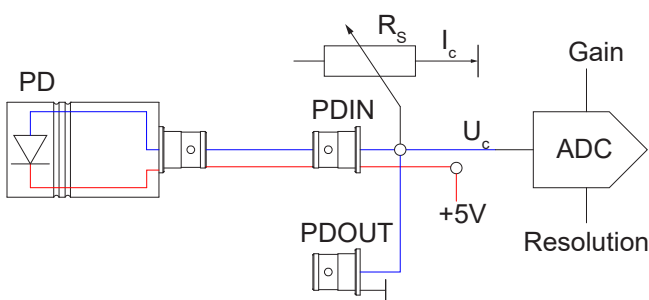
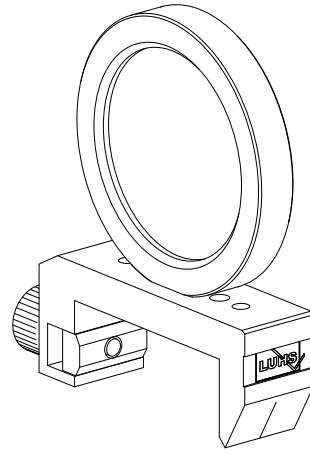


Fig. 33: Photodiode schematic

The photo voltage U_c is internally connected to a high precision ADC from which the microprocessor reads the value of the of U_c and the value of the load resistor R_s and displays their values on the touch screen of the MK2 controller.

It must be noted that the measured power is correct only if the entire light beam hits the detector. Based on the selected load resistor the sensitivity will be high for higher resistors but the rise and fall time will be longer. For fast signals, a low resistor should be used, however the sensitivity will be lower.

3.7 Module 7 Translucent screen



In a round holder a sheet of translucent paper is fixed with a retaining ring. This component is useful to image and visualize optical rays. Furthermore, the translucence allows the convenient photographic recording from the opposite side with digital cameras for a quick picture for the students measurement report.

3.8 Module 8 Digital Diode Laser Controller MK1



This microprocessor operated device contains a laser diode controller and a photodiode amplifier. A touch panel display allows in conjunction with the digital knob the selection and setting of the parameters for the attached laser or photodiode.

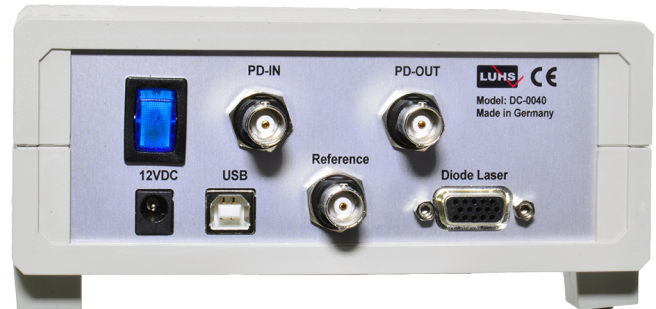


Fig. 34: Digital Diode Laser Controller MK1

The laser diode module is connected via the 15 pin HD SubD panel jacket (LD). The controller reads the EEPROM of the laser diode and sets the required parameter accordingly. The MK1 is powered by an external 12V/ 1.5 A wall plug supply. A USB bus allows the connection to a computer for remote control. Furthermore, firmware updates can be applied simply by using the same USB bus.

The MK1 provides an internal modulator which allows the periodic switch on and off of the diode laser. A buffered synchronization signal is available via the BNC jacket (MOD). Furthermore, the duty cycle of the modulation signal can be varied in a range of 1...100 % to enable the measurement of

thermal sensitivity of the optically pumped laser crystal. The controller is equipped with industrial highly integrated circuits for the bipolar Peltier cooler (Maxim, MAX 1978) as well as for the injection current and modulation control (iC Haus, iC-HG) of the attached laser diode.

The photodetector is connected via the provided BNC cable to the PD-IN BNC panel jack. The analogue photo voltage is available at the PD-OUT panel jack.

When the LED or laser is operated in modulated mode, the reference modulator signal is available at the "REFERENCE" BNC connector. Further detailed specifications are given in the following section of the operation software.

3.8.1 Diode laser controller screens

When the external 12 V is applied, the controller starts displaying the screen as shown in the figure below.

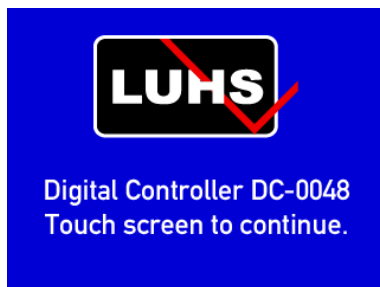


Fig. 35: Start screen

Laser Safety

The first interactive screen requires the log in to the device since due to laser safety regulations unauthorized operation must be prevented. In general, this is accomplished by using a mechanical key switch. However, this microprocessor operated device provides a better protection by requesting the entry of a PIN.

After entering the proper key, the next screen is displayed and the system is ready for operation.



Fig. 36: Authentication screen

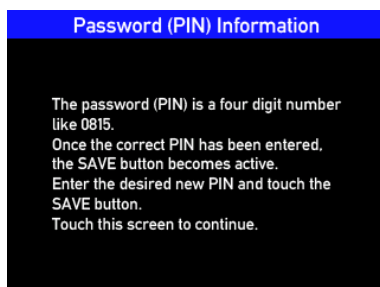
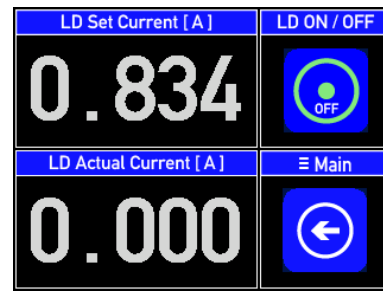
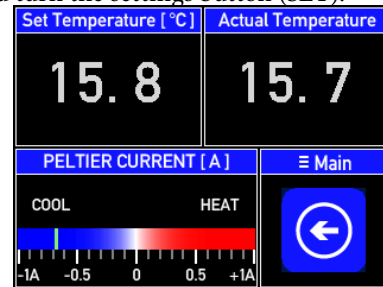


Fig. 37: Information for the password

Main Screen

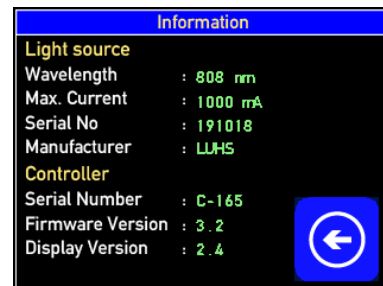


For immediate "Laser OFF" just tap the yellow button. To set the injection current simply tap the injection current display and turn the settings button (SET).



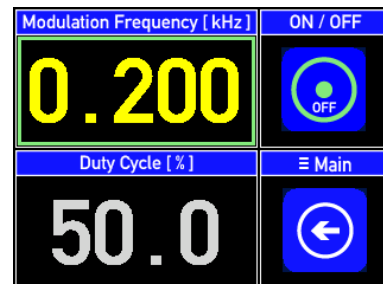
The same is true also for the "Set Temperature" section. When in operation and connected to the laser diode the actual temperature is shown in the "Actual Temperature °C" section. Furthermore the actual current of the Peltier element is shown in such a way, that cooling or heating of the element can be observed.

Information screen



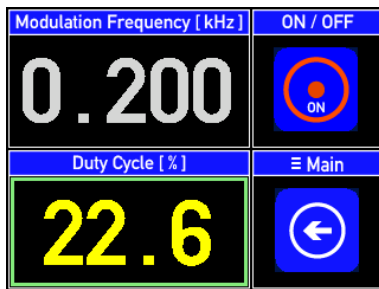
When tapping the Device Info button of the main screen this screen comes up. It again reads and displays the information stored in the EEPROM of the attached diode laser. If an entry exceeds the maximum or minimum limit value retrieved from the EEPROM of the attached diode laser the entry is reversed to the respective minimum or maximum value.

Modulation settings



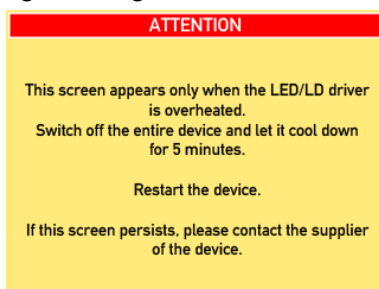
The diode laser can be switched periodically on and off. This is for a couple of experiments of interest. By tapping the display of the modulation frequency, the entry is activated. Turning the settings knob will set the desired frequency value. The modulation becomes active, when the Modulator ON/OFF button is tapped.

Duty Cycle settings



For some experiments it is important to keep the thermal load on the optically pumped laser crystal as low as possible or to simulate a flash lamp like pumping. For this reason, the duty cycle of the injection current modulation can be changed in a range of 1...100 %. A duty cycle of 50% means that the OFF and ON period has the same length. The set duty cycle is applied instantly to the injection current controller.

Overheating warning

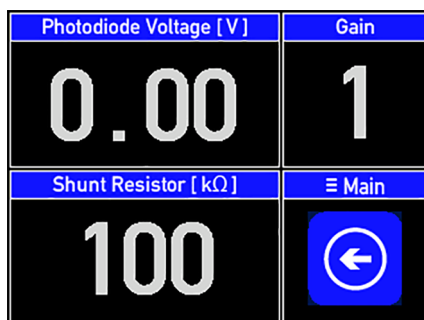


This screen you should never see. It appears only when the chip of the injection current controller is over heated. Switch of the device, wait a couple of minutes and try again. If the error persists, please contact your nearest dealer.

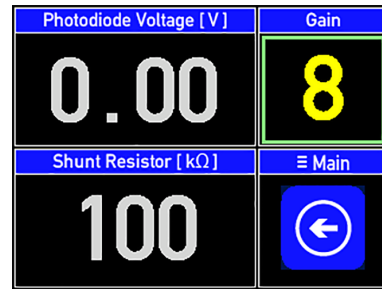


This screen is self-explanatory and appears either when no laser diode is connected or the data reading from the EEPROM is erroneous.

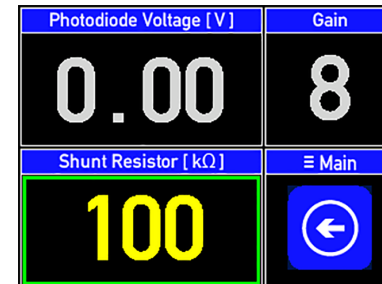
Photodetector Screens



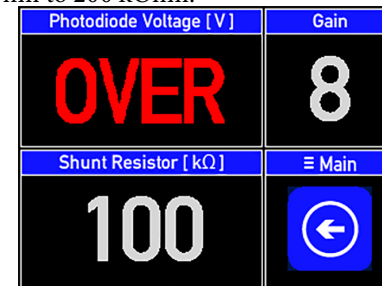
The photodiode page displays the measured photo voltage, the selected shunt resistor and the chosen gain.



Tapping the gain display field switches the gain from 1, 2, 4 and 8.

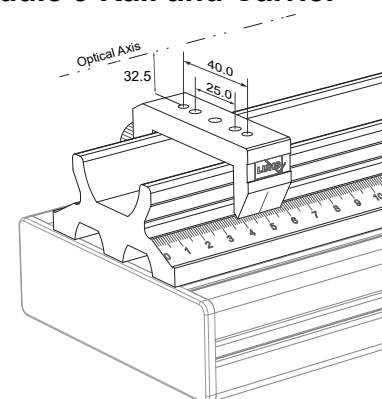


Activating the shunt resistor display field lets one set the shunt resistor by turning the digital knob. The value ranges from 1 kOhm to 200 kOhm.



If the photo voltage exceeds the inter reference voltage of 2.048 V the display shows the overload state. Reduce the gain or the shunt resistor. If the overload state remains although both values are set to minimum values, the injection current should be reduced as well.

3.9 Module 9 Rail and Carrier



The rail and carrier system provides a high degree of integral structural stiffness and accuracy. Due to this structure it is a further development optimized for daily laboratory use. The position of the carrier on the optical rail can be precisely adjusted thanks to the attached ruler and the markings on the carrier. The optical height of 32.5 mm above the carrier surface and the mounting holes are compatible with all other systems like from MEOS, LUHS, MICOS, OWIS and LD Didactic. Consequently, a high degree of system compatibility is achieved.

4.0 Experiments

4.1 Laser diode output versus injection current and temperature

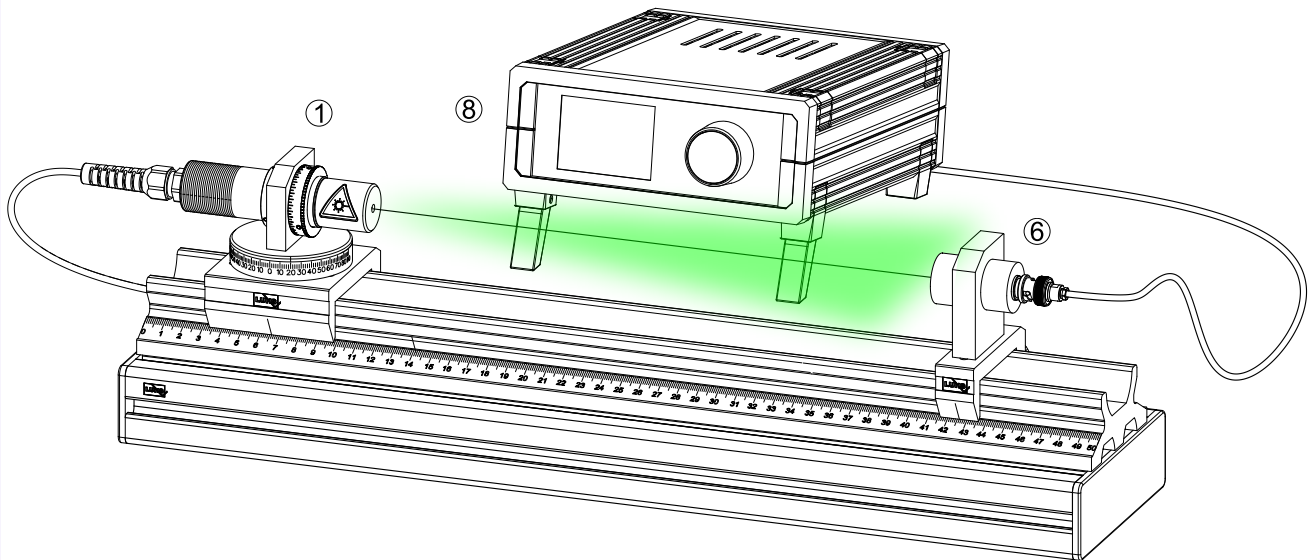


Fig. 38: Set-up to measure the relative output power

The task of this experiment is to measure the optical power versus the injection current for a set of fixed temperatures. To measure the output power in relative units the photodetector module (6) is placed onto the rail as shown in Fig. 38. The photodetector (6) is connected to the Laserdiode Controller (8). "It must be noted that the measured power is correct only if the entire light beam hits the detector. Based on the selected load resistor the sensitivity will be high for higher resistors but the rise and fall time will be longer. For fast signals, a low resistor should be used, however the sensitivity will be lower." on page 8 The output of the controller is connected either to an oscilloscope or to a digital multimeter which is set to voltage measurement. However also the builtin photodetector section can be used to read the photo voltage. For a set of different temperatures such as 10, 30 or 40°C the voltage U_m of the signal box is recorded.

Wavelength	515	nm	
Temperature	30	°C	
$S(\lambda)_{rel}$	0.38		Fig. 32
$S(\lambda)$	$S(\lambda)_{rel} \cdot 0.38$	A/W	
Injection current [mA]	Voltage U_m	$R_L [\Omega]$	$P_{opt} [mW]$

Table 2: Suggestion for a measurement sheet

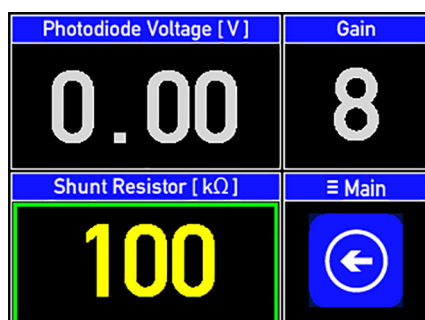


Fig. 39: The inbuilt photodetector of the Laserdiode Controller

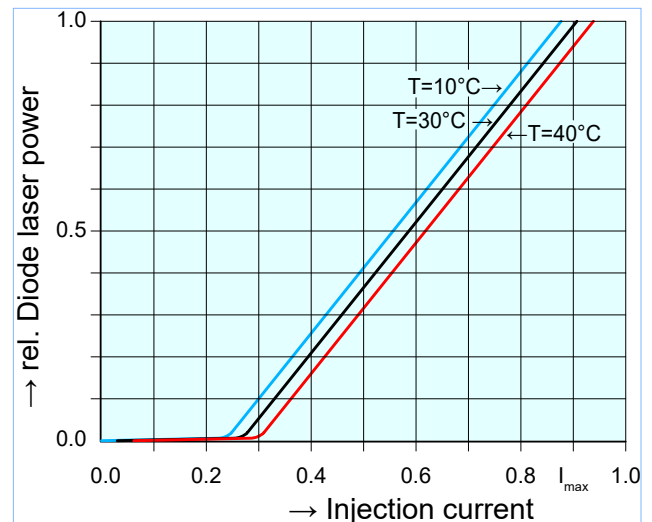


Fig. 40: Laser power versus injection current and temperature as parameter

Note:

Adjust the distance between the photodetector and the diode laser carefully, ensuring that the detector does not become saturated by the intense light. The power you measure will only be a small portion of the total output, as merely a fraction of the emitted laser power actually reaches the detector's surface.

4.2 Spatial Beam Distribution

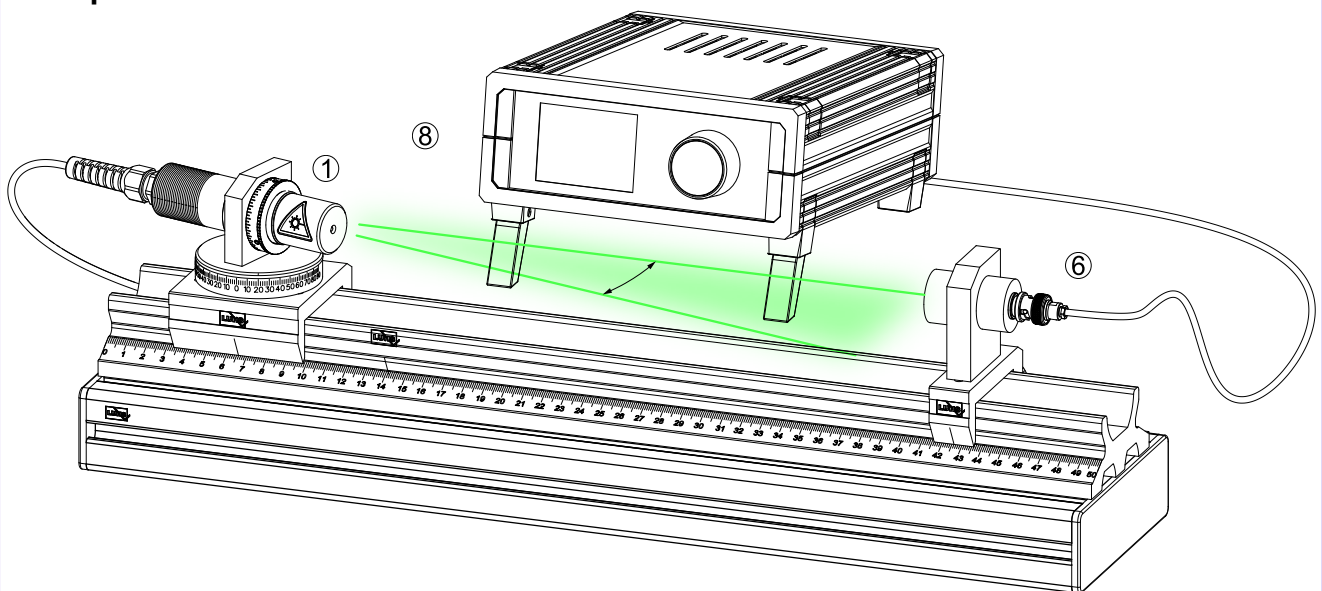


Fig. 41: Set-up to measure the spatial beam distribution

With the above set-up the beam geometry of the laser diode will be measured. The module 1 (laser diode with two axes rotational stage) and the photo detector (module 6) are used.

The laser diode is capable of being rotated both around its optical axis and perpendicular to it. Rotation around the optical axis is used to align the elliptical beam profile of the diode with the plane of the other rotational stage. By turning this stage, the angle-dependent intensity distribution of the laser diode's emission is measured.

The photodetector (6) is linked to the diode laser controller (1), where the photovoltage is shown.

It is essential to ensure that the detector does not become saturated by the laser light.

Naturally, the output from the diode laser controller can be linked to an oscilloscope. In such a scenario, the modulator within the control unit can be enabled to generate a rectangular AC waveform.

Within the same set-up the dependence of the laser power versus injection current and temperature can be measured as well.

In addition the behaviour of the laser diode is measured when it is modulated by the internal modulator with a rectangular amplitude. For this purpose the modulator is activated within the selection menu (3.8.1) of the controller (8). The provided TTL signal of the modulator of the controller (8) can be connected to the oscilloscope and used as trigger source.

4.3 Wavelength Measurement with a Spectrometer

From the previous chapters it is known that the wavelength of a laser diode is determined by the maximum gain and the optical length of its resonator, which in turn depends on the temperature and the optical density inside the resonator relying on the injection current.

The goal of this experiment is the measurement of these relations.

For each couple of injection current and temperature the

curve for constant wavelength is drawn. Using the linear regression the coefficients $\alpha(I)$ and $\alpha(T)$ are derived.

It is necessary to recognize that the output power of the laser diode is influenced by temperature, which must be measured beforehand. Additionally, caution should be exercised to avoid saturating the detector with excessively high laser power.

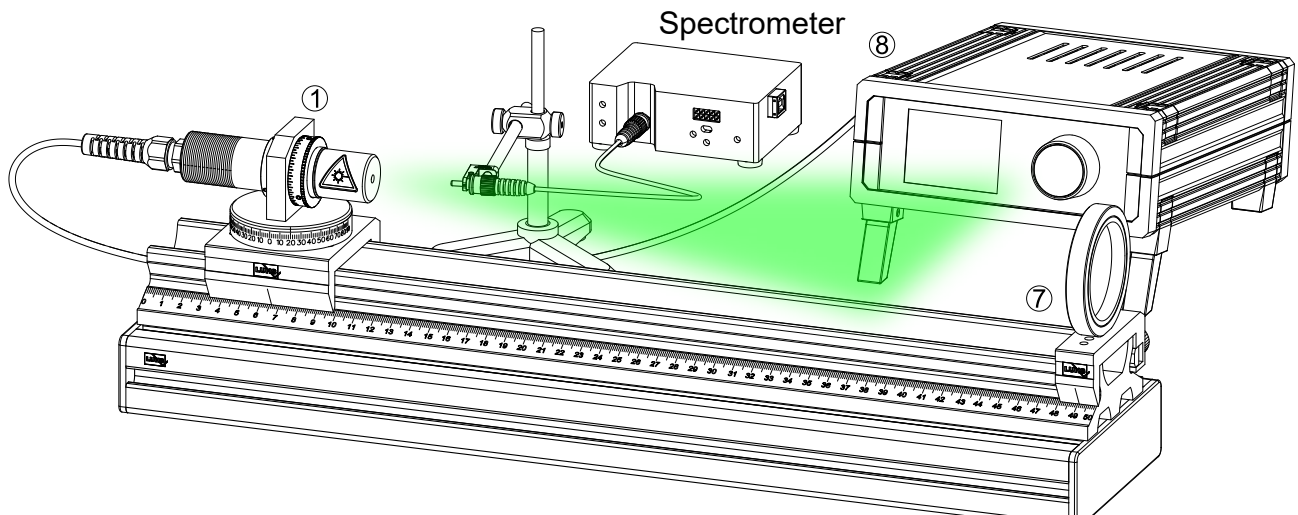


Fig. 42: Setup to measure the emission wavelength with a spectrometer

If the optional spectrum analyser is accessible, a range of further experiments can be performed. The process for deriving the curve at a constant wavelength is conducted in the same manner. Furthermore, the spectrum analyser enables the measurement of the complete emission spectra of the laser diode across various temperatures and injection current levels.



Fig. 43: Fiber coupled Spectrometer

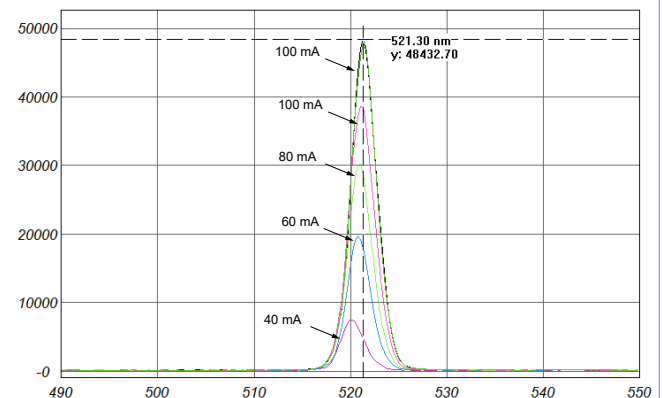


Fig. 45: Wavelength versus injection current at constant temperature

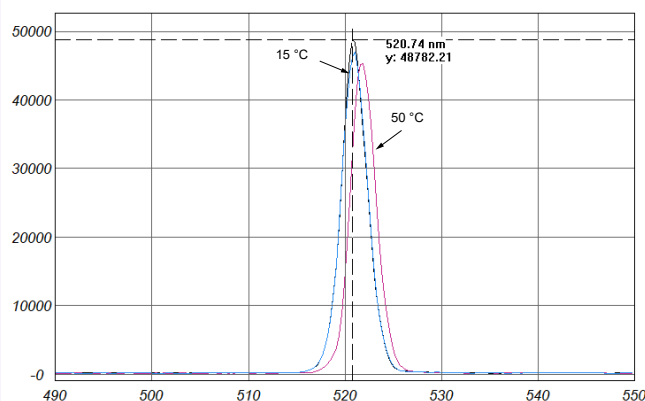


Fig. 44: Wavelength versus Temperature at constant injection current

4.4 Polarisation

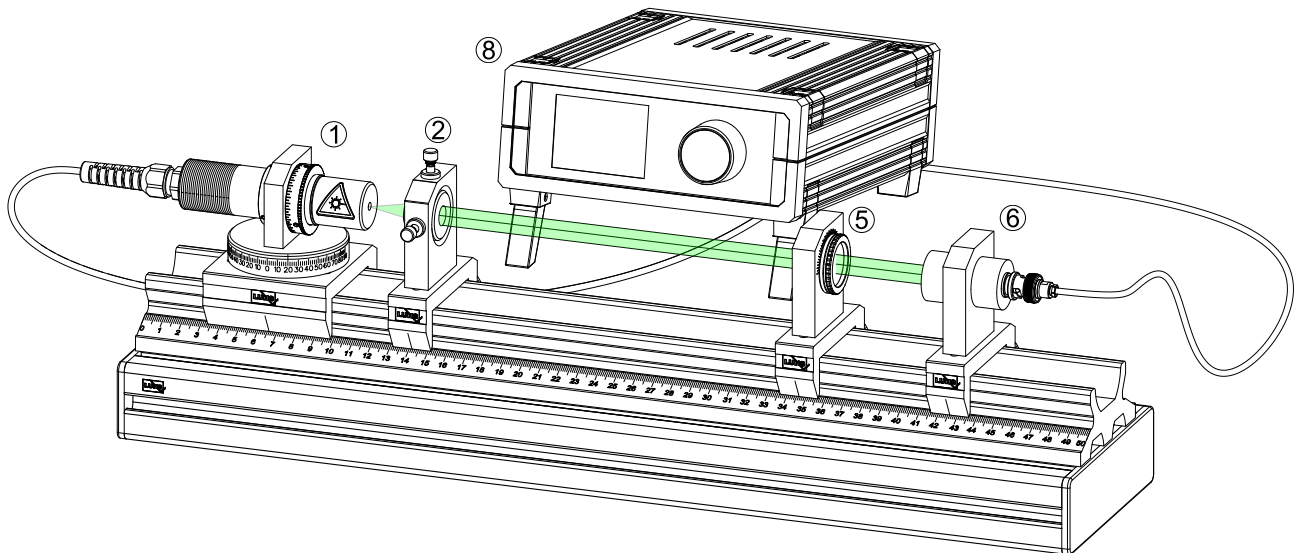


Fig. 46: Set-up for measuring the polarisation of the laser beam

To the previous set-up the module 2 and module 5 are added. The module 5 consists of a mounting plate with angular scale for rotating and reading the angle position of the polariser mounted into the plate.

Take care that the detector will not be saturated. To obtain unambiguous polarisation states with respect to the polarisation analyser the laser light of the diode is collimated by means of the module 2 containing the focussing optics. The polarisation analyser is turned to a position for a sufficient signal. Now the injection current is varied and the intensity behind the analyser is measured. Of major interest is the region around the threshold, where the diode turns from the LED into the laser operation.

4.5 Beam shaping

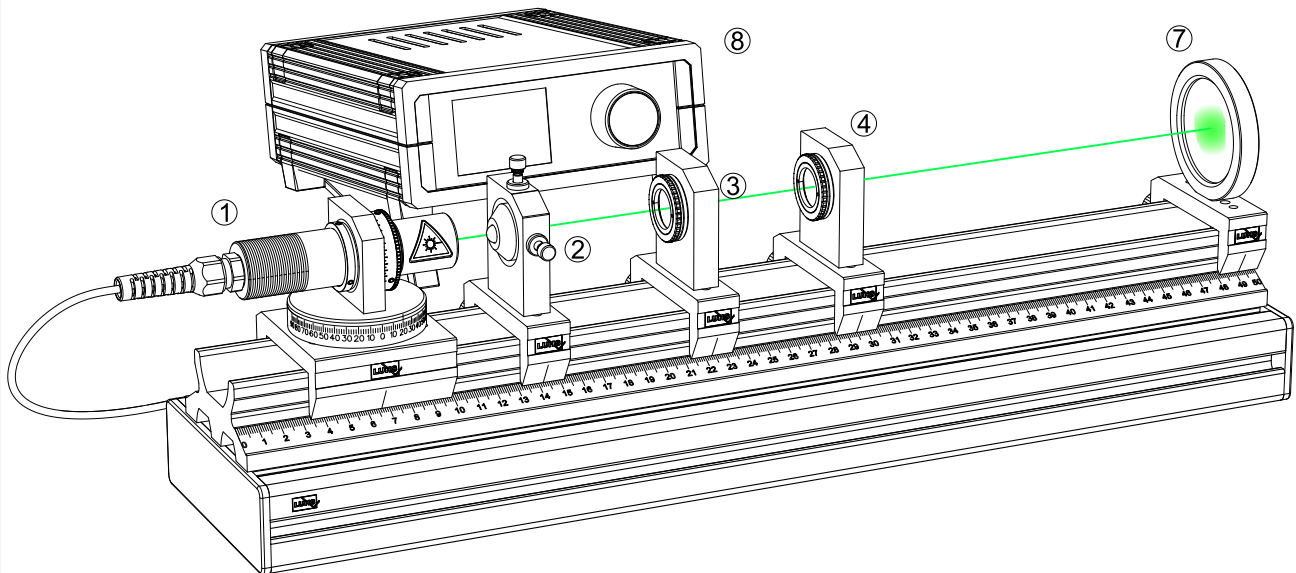


Fig. 47: Set-up for laser beam shaping

From the basics and carried out measurements it is known that the emitted beam of the laser diode exhibits a more or less strong divergence which in addition possesses a significant astigmatism.

Within this optional experiment different sets of lenses shall be used to correct the beam shape.

Without optics which corrects for these errors, the use of diode lasers is very limited. Applications of laser diodes are only successful if one is able to transform the beam into the desired shape.

For this reason in this experiment three different optical elements are used:

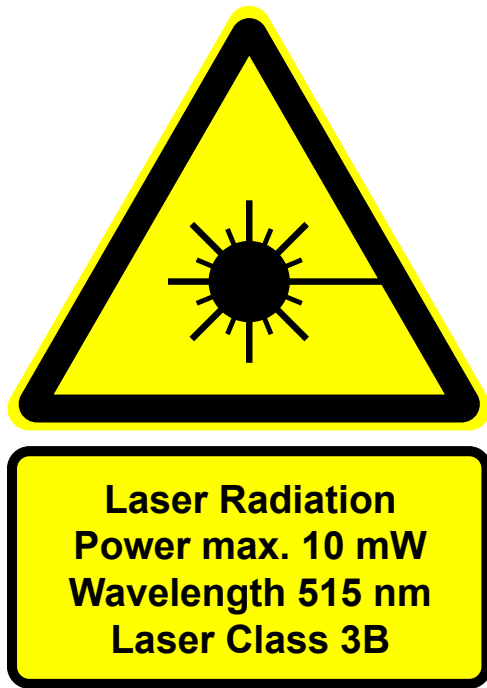
module 2	collimator lens	$f = 4.5 \text{ mm}$
module 3	cylindrical lens	$f = -15 \text{ mm}$
module 4	cylindrical lens	$f = 45 \text{ mm}$

With these elements a series of different layouts can be realised:

e.g.

- beam shaping with crossed cylindrical lenses
- with collimator 1 and cylindrical lens telescope
- generation of almost round beam with cylindrical lens 3, and cylindrical lens 4.
- creation of a laser line with collimator 2 and module 3

5.0 Laser safety



This set-up contains a diode laser which is only suitable for laboratory applications.

With the individual modules in the assembled state, laser radiation (semiconductor laser) can be produced at 805 nm with a maximum power of 30 mW.

The complete assembled laser is therefore a product which exhibits the power characteristics of a Class 3B laser. Since the EXP01 is a laser system formed from combined modular elements and can therefore be modified in a number of different ways, the operator of this system must ensure that the safety requirements are met.

The manufacturer only provides a guarantee for the individual modules, but does not accept any responsibility for cases of damage which arise due to the combination of the modules. The user must observe the laser safety regulations, e.g. **DIN VDE0837 or IEC 0837**.

In these guidelines of February 1986 the following points are listed for the operation of laser equipment in laboratories and places of work.

Laser equipment in laboratories and places of work

Class 3B laser equipment

Class 3B lasers are potentially hazardous, because a direct beam or a beam reflected by a mirror can enter the unprotected eye (direct viewing into the beam). The following precautions should be made to prevent direct viewing into the beam and to avoid uncontrolled reflections from mirrors:

a.) The laser should only be operated in a supervised laser area

b.) Special care should be taken to avoid unintentional reflections from mirrors

c.) Where possible the laser beam should terminate on a material which scatters the light diffusely after the beam has passed along its intended path. The colour and reflection properties of the material should enable the beam to be diffused, so keeping the hazards due to reflection as low as possible.

Note: Conditions for safely observing a diffuse reflection of a Class 3B laser which emits in the visible range are : Minimum distance of 13 cm between screen and cornea of the eye and a maximum observation time of 10s. Other observation conditions require comparison of the radiation density of the diffused reflection with the MZB value.

d.) Eye protection is necessary if there is a possibility of either direct or reflected radiation entering the eye or diffuse reflections can be seen which do not fulfil the conditions in c.).

e.) The entrances to supervised laser areas should be identified with the laser warning symbol

MZB means Maximum Permissible Radiation (Maximal zulässige Bestrahlung) and it is defined in section 13 of DIN/VDE 0837.

Special attention is drawn to point 12.4 of DIN VDE0837:

Laser equipment for demonstration, display and exhibition purposes

Only Class 1 and Class 2 lasers should be used for demonstrations, displays and exhibitions in unsupervised areas. Lasers of a higher class should then only be permitted if the operation of the laser is controlled by an experienced and well trained operator and/or the spectators are protected from radiation exposure values which does not exceed the applicable MZB values.

Each laser system, which is used in schools for training etc. should fulfil all the applicable requirements placed on class 1 and class 2 laser equipment; also, it should not grant persons access to radiation which exceeds the applicable limits in Class 1 or Class 2.

