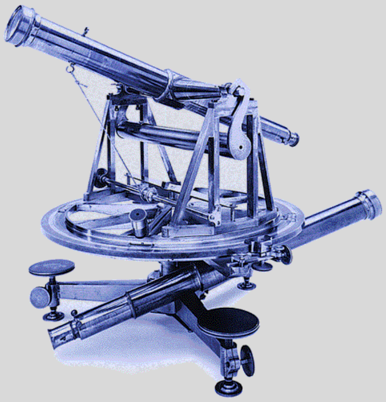
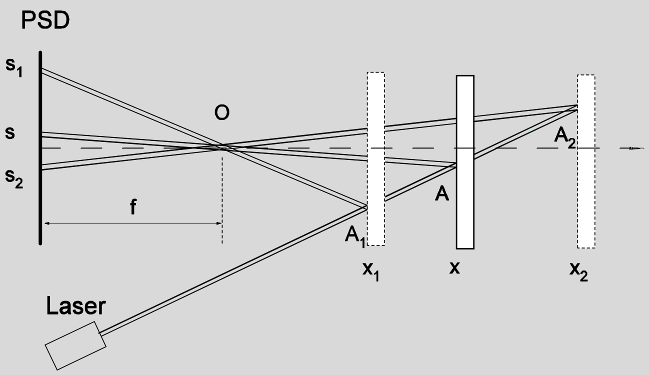
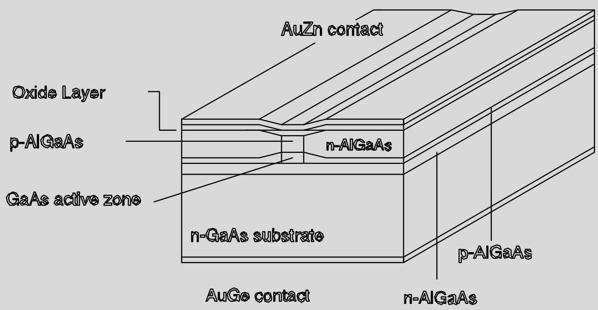


EXP21 Laser Triangulation

MEOS





1 INTRODUCTION 3

2 BASICS 4

2.1 Laser diodes 4
2.1.1 Semiconductor laser 5
2.1.2 Resonator and beam guidance 6
2.1.3 Divergence and intensity distribution 6
2.1.4 Polarisation 7
2.1.5 Spectral properties 7
2.1.6 Optical power 8

2.2 Semiconductor– and Position Sensing Detectors 8
2.2.1 Principles of Semiconductor Detectors 8
2.2.2 Principles of Position Sensing Detectors 10

2.3 Range Determination 11

3 EXPERIMENTS 12

3.1 Description of the Modules 12

3.2 Experimental set-up and measurements 13
3.2.1 Calibration 13
3.2.2 Measurements 13

1 Introduction

Triangulation is a well known technique of the classical optics, especially used in geodesy. Triangulation is the process of finding a distance to a point by calculating the length of one side of a triangle, given measurements of angles and sides of the triangle formed by that point and two other reference points. In the third century BC already, the masterminded Greek Eratosthenes made the first attempt to measure the circumference of the globe. Using triangulation and solar observation to measure the distance along a meridian, he calculated a circumference of 250.000 stadia, which translates to about 38.000 kilometers. This value differs from the actual value of 40.056 km only by 5%!

In the 18th and 19th century the construction of triangulation instruments, so called theodolites, was more and more refined. A masterpiece of those time was developed by Georg von Reichenbach in 1805 (Fig. 1) and was an archetype for all instrument makers for more than hundred years.

Fig. 1: Theodolite from 1805

Nowadays geodesy and navigation is performed with the help of satellite data basing on triangulation measurements. After the invention of the laser, metrology and geodesy have got a measuring tool for achieving data in an unsurpassed accuracy.

The combination of laser and triangulation created a new field of application for the laser distance measurement. In principle the laser distance measurement can be classified to three major sections where each one uses particular properties of the laser. For distance or length measurement with interferometer the low divergence and the coherence of the laser is used. In laser range finding application the low divergence of the laser beam and the defined speed of light is used. In the case of laser triangulation only the low divergence of the laser beam is exploited. Each technique has a particular measuring range and accuracy.

1. Triangulation 1 to 50 cm with a relative accuracy of 10^{-3}
2. Interferometer up to 50 m with a relative accuracy of 10^{-8}
3. Range Finder 1 m up to several km with a relative accuracy of 10^{-3}.

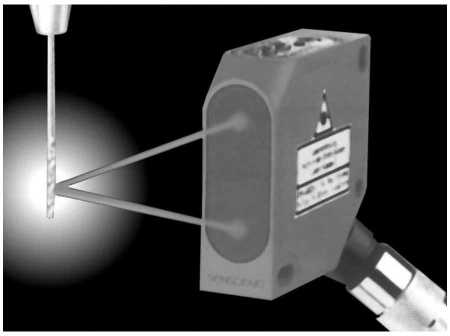


Fig. 2: Modern Laser Triangulation Sensor used in Industry

Optical distance measurement is used in a wide variety of industrial, commercial, and research applications. Laser triangulation in particular is qualified for distance measurement in industrial applications (Fig. 2). Although laser triangulation provides a measuring range from 1 to 50 cm, the triangulation technique cannot cover the entire range because the principle of the measurement is based on optical imaging. However the costs of a triangulation head compared to Laser interferometer are so small that one can use a number of units to cover the desired range. In the automobile industry for example, it is common to equip a car body measuring cabinet with nearly one hundred of triangulation heads in defined positions. The car is driven into the cabinet and in a very short time the dimensions of interest can be measured. Since the laser triangulation works contactless a lot of other applications in automated production processes exist.

Within this workshop the principle of the Laser triangulation is studied and applied at different objects mounted on a manual driven translation stage with micrometer readout.

2 Basics

Laser triangulation falls into the general category of non-contact range measurement. A triangulation sensor may provide the same information as a linear variable differential transformer or contact probe, but without touching the object to be measured. The system works by projecting a beam of light onto the object of interest. From this target the scattered or reflected light is collected by a lens which is typically located adjacent to the laser emitter. The collected light falls on a position sensing detector. From the light spot position on the detector the distance of the object from the reference point can be calculated. As the point of light, falling on the object, moves closer to or farther from the reference point, the spot position on the detector changes.

There are many factors to consider when specifying a laser triangulation system. They include maximum range, detector sensitivity, target reflectance and specularity, accuracy and resolution, environmental conditions, and sample rate.

For diffuse targets, the higher the reflectance of the target, the better a sensor's performance will be. Materials such as wood, paper, or white paint are mainly diffuse targets that work well at all distances. In addition to the amount of light a surface reflects, the way in which light is reflected can affect an optical sensor's performance. Many surfaces are partially specular and partially diffuse. These can be difficult to measure, and the amount of light or returned to a sensor may vary greatly with the angle of the target surface.

The accuracy of a sensor is a measurement of the difference that can be expected between a sensor's reading and the actual distance measured. The resolution is the smallest change in distance that a sensor can detect, and is typically a smaller value than the accuracy error. Accuracy may be affected by temperature, target reflectance or ambient light, which generally will not affect the resolution. For many applications, resolution is more important than absolute accuracy.

Repeatability is a measure of sensor stability over time. Typically, sample to sample repeatability will be lower for very fast sample rates, since less time is used to average the measurement. As the sample rate is lowered, repeatability will improve, but this does not continue indefinitely. Beyond some slower sample rate, repeatability will start to worsen as long term drift in the components and temperature changes cause changes in the sensor's output.

Other specifications which may be important are the laser spot size and the divergence of the beam. Some applications require a small spot for high-resolution measurement while others require a larger diameter spot for averaging rough surfaces. A small, focused laser spot will help to resolve tiny features on a target's surface. A large spot will reflect off larger areas which may contain features at several different heights. The reported distance would be the average of those individual heights.

A triangulation system can be broken down into three subsystems: transmitter, receiver, and electronic processor.

The transmitter, typically a laser diode with beam-shaping optics, projects a beam that illuminates the target object. The most popular transmitter at present is an inexpensive, low-power 670 nm laser diode with a visible beam. The optics used to manipulate the laser diode output creates a small spot at the standoff distance. The size of the spot is dictated by the optical design, and influences the overall system design by setting a target feature size detection limit. For instance, if the spot diameter is 1 mm it will be difficult to resolve a lateral feature <1 mm.

The receiver/detector subsystem gathers the light reflected off the target and images the light onto a detector. The detector then reports the spot position to the processor, which determines the range. Of the many types of optical detectors available, two are most commonly used for laser triangulation sensors: position-sensing detectors (PSDs), and pixelized array detectors, also known as arrays. Each type has limitations and capabilities.

Processing electronics vary according to the type of detector used in the sensor. PSDs provide two electrical current outputs that are proportional to the position of the imaged spot on the detector. After subtraction and normalization of these values the spot’s position on the detector can be determined. Another information that can be derived from the PSD is that the two outputs can be summed up to measure the total optical power on the detector.

2.1 Laser diodes

Laser diodes are a special class of lasers. They differ from „conventional“ lasers in two points: 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. Generally for conventional lasers the mirrors are very large compared with the beam diameter. The size of a laser mirror (crystal gap area of the active zone) of the laser diodes lies in the order of a few micrometers in both dimensions, about 3 orders of magnitude smaller than mirrors of conventional lasers. By passing such small features the laser light sustains diffraction effects which cause non-Gaussian beam shapes.

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. The two energy bands are called valence (energetically lower) and conduction band (energetically higher band) respectively. Because of the thermal energy some electrons will leave the valence band and populate the conduction band. If we succeed to populate the conduction band with electrons and to have a valence band which is not completely occupied by electrons (Fig. 3) electrons may relax from the conduction band back to the valence band. That way a photon is generated. By absorption of a photon the inverse process is also possible.

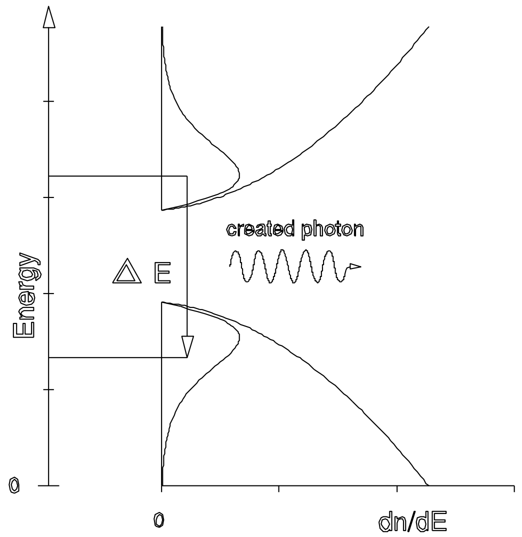


Fig. 3: Population inversion in a semiconductor for T > 0

Figure 3 shows the situation of such 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. 3 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 donators and acceptors. By the connection of the doted 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 aluminium gallium arsenide (AlGaAs), where a portion of the gallium atoms has been replaced by aluminium 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 stress free it is important that the lattice structure of the host crystal (lattice matching) coincides fairly well with the lattice 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.

2.1.1 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

The first laser was basically made of highly doted GaAs (Fig. 4). A threshold current of 100 kA/cm^2 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/cm^2 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/cm^2 and working in the pulse mode at room temperature was possible (Fig. 5).

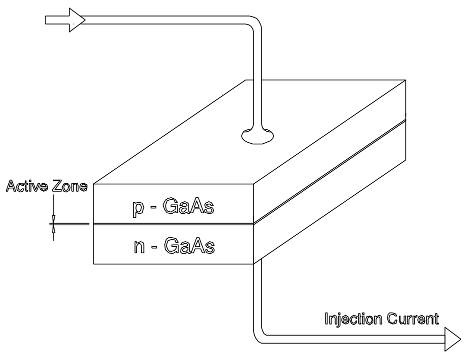


Fig. 4: Simple laser diode around 1962, working at 70 K and with 100 kA/cm^2 in the pulse mode.

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/cm^2.

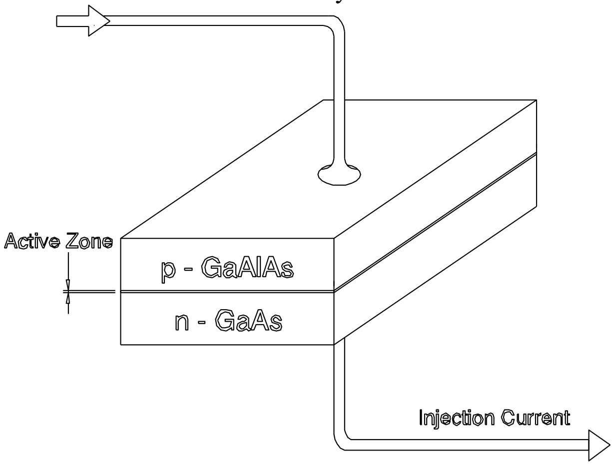


Fig. 5: Simple-hetero structured laser around 1968, working at 8 kA/cm^2 in pulse mode at room temperature.

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/cm^2. Until today nearly all commercially sold laser diodes are built up on the double hetero structure principle. (Fig. 6 and 7).

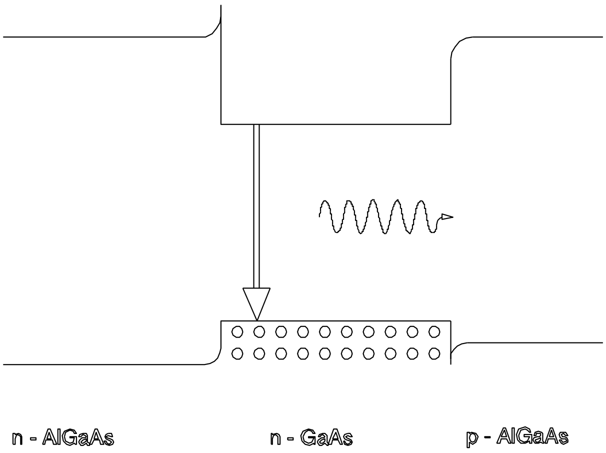


Fig. 6: Energy band diagram of a N n P - double hetero structure.

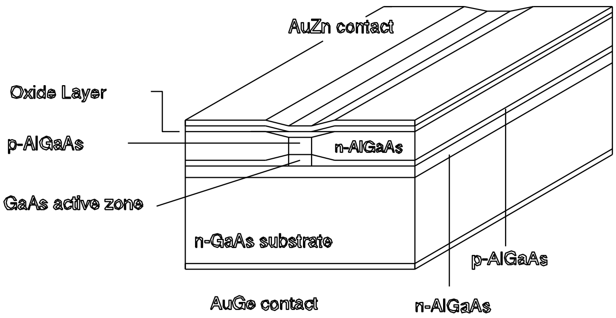


Fig. 7: „Buried“ hetero structure. The active zone has been buried between some layers which ensure an optimal beam guidance in the zone.

2.1.2 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 (λ = 632 nm) with a typical resonator length of 20 cm this ratio is 3 10^8. 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.

2.1.3 Divergence and intensity distribution

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 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. (Fig. 8).

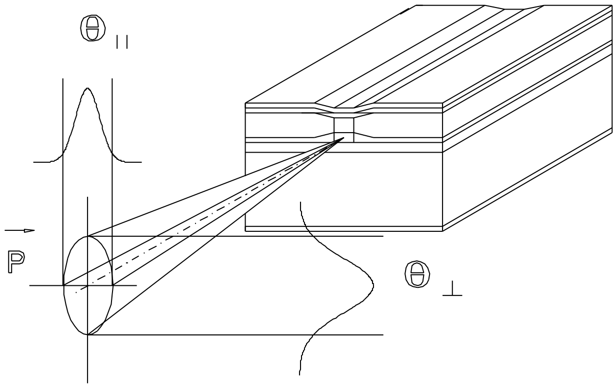


Fig. 8: Elliptical beam profile of a diffraction limited laser diode in the far field (some meters).

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 10-30° 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 (Fig. 9). 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).

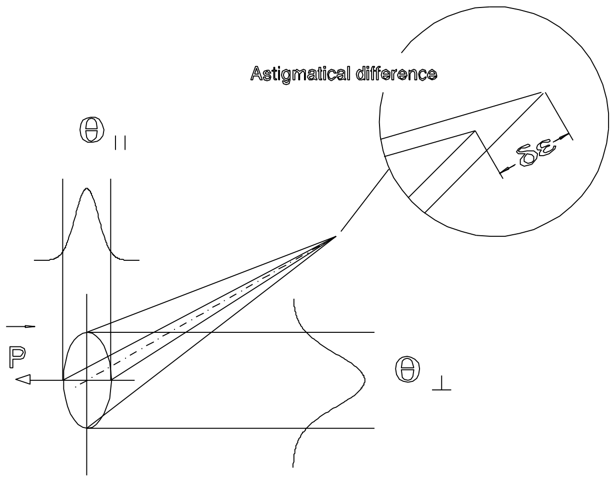


Fig. 9: Astigmatic difference δε

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.

2.1.4 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. 11 and 12).

2.1.5 Spectral properties

Another property of the diode laser is the dependence of its wavelength on the temperature (about 0.25 nm/K) and on the injection current (about 0.05 nm/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.

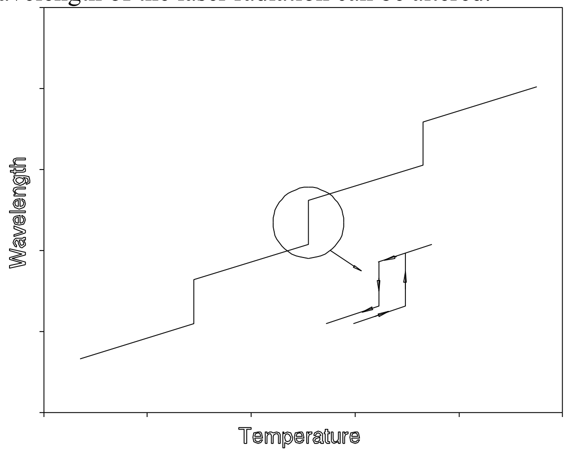


Fig. 10: Emission wavelength as a function of the crystal temperature of the laser diode and hysteresis.

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 µm), the jump is about 0.3 nanometer. 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. 10).

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. 11).

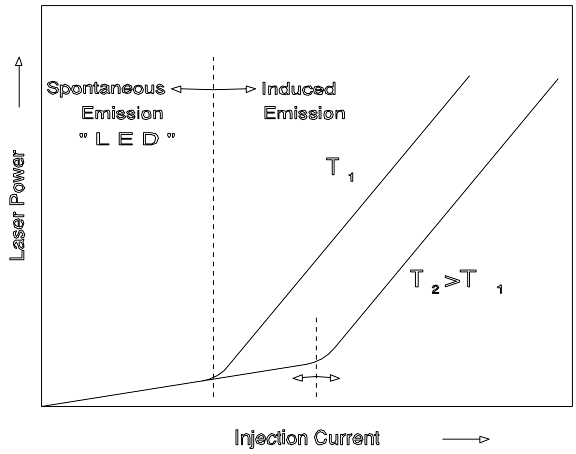


Fig. 11: Laser power versus injection current with the temperature T as parameter

2.1.6 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 below 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.

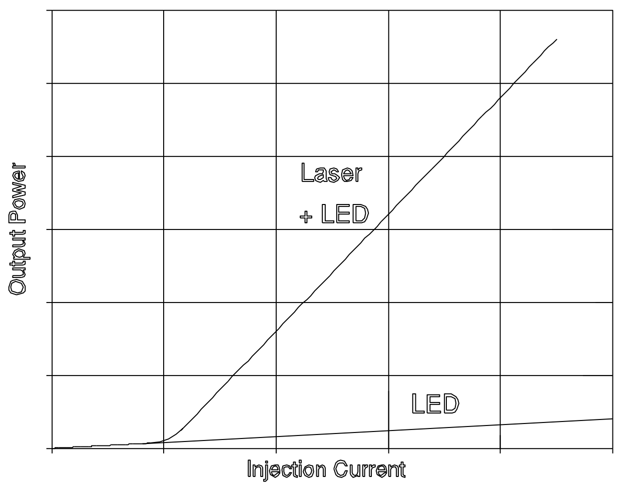


Fig. 12: Output power of the laser diode as a function of the injection current

2.2 Semiconductor– and Position Sensing Detectors

In the experiment “Laser Triangulation” a Position Sensing Detector (PSD) is used. First the properties of semiconductor detectors in general will be discussed. Then the principles of operation of PSDs will be presented.

2.2.1 Principles of Semiconductor Detectors

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.

$$E_p = \hbar w \geq E_g$$

In this case an arriving photon can stimulate an electron to pass from the valence band to the conduction band. (Fig. 13).

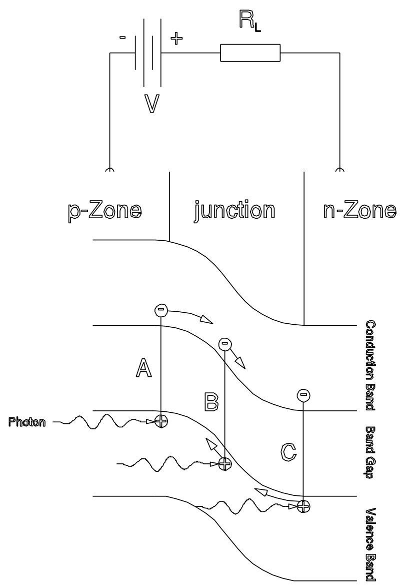


Fig. 13: Absorption of a photon with subsequent transition of the stimulated electron from the valence band to the conduction band

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 $\frac{P_o}{\hbar\omega}$ photons will hit the detector as $\hbar w$ 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 line 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.

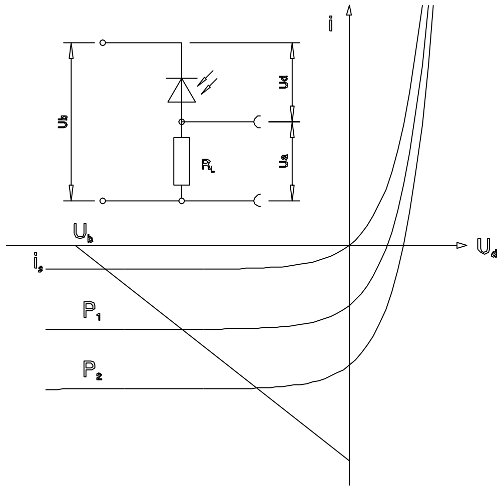


Fig. 14: Characteristic line of a photodiode in the photoconductive mode

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

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 650 nm wavelength is applied. Therefore a silicon detector is used.

2.2.2 Principles of Position Sensing Detectors

Position Sensing Detectors "PSD" are silicon photodiodes that provide an analogue output directly proportional to the position of a light spot on the detector active area. The PSD allows to simultaneously monitor position and light intensity.

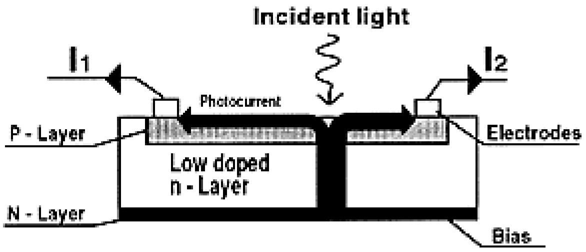


Fig. 15: Layer Structure of a PSD

The Position Sensing Detector consists of n-type silicon substrate with two resistive layers separated by a p-n junction. The front side has an ion implanted p-type resistive layer with two contacts at opposite ends. The back side has an ion implanted n-type resistive layer with a contact covering the whole layer. In 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, a low doped n-layer (Fig. 15). 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.

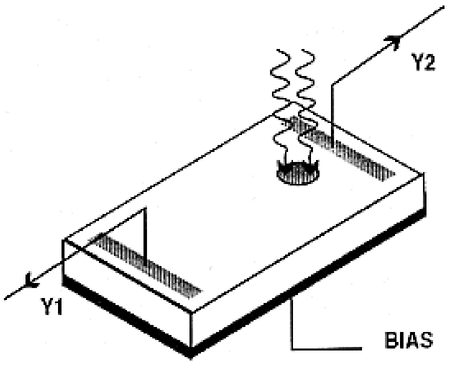


Fig. 16: Incident Photons generate a Photocurrent

The electrodes are placed at opposite ends of the p-type resistive layer (Fig. 16). A light spot within the spectral range of silicon will generate a photocurrent which flows from the incident point through the resistive layers to the electrodes. The resistivity of the ion implanted layer is extremely uniform so the photo-generated current at each electrode is inversely proportional to the distance between the incident spot of light and electrodes. The PSD outputs track the motion of the centroid of power density.

The photoelectric current generated by the incident light flows through the device and can be seen as an input bias current divided into two output currents. The distribution of the output currents shows the light position on the detector.

2.3 Range Determination

For determining range via triangulation, the baseline distance between source and sensor as well as sensor and source angles are used in theory. In practice however, this is difficult to achieve because the baseline separation and angles are tricky to measure accurately. Therefore another technique is discussed here.

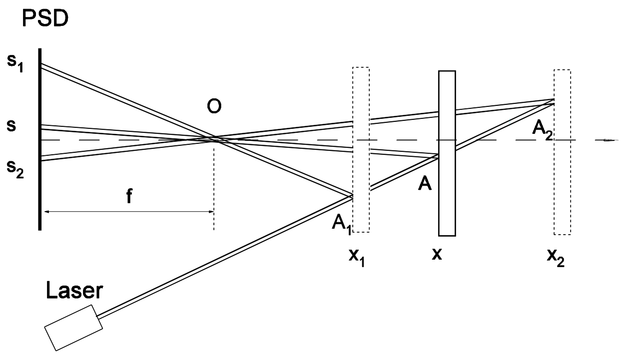


Fig. 17: Principle of Laser Triangulation

In Figure 17 the laser is positioned so that the path of the laser and the optical axis (dashed line) form a vertical plane. Point A is the target of interest and its position x has to be determined. s is the projection of point A on the PSD plane. A_1 and A_2 are two points used for the calibration of the system; x_1, x_2, s_1 and s_2 are known.

The determination of position x of the target is achieved as follows: In a coordinate system with origin O the line sA passing through O is represented by

$$y = \frac{s}{f} \cdot x \qquad \text{Equ. 1}$$

with the focal length f. The laser path is of the form

$$y = m \cdot x + c \qquad \text{Equ. 2}$$

The slope m can be written as

$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{s_2 \cdot x_2 - s_1 \cdot x_1}{f\,(x_2 - x_1)} \qquad \text{Equ. 3}$$

and the offset c as

$$c = y_2 - m \cdot x_2 = \frac{s_2 x_2}{f} - m \cdot x_2 \qquad \text{Equ. 4}$$

Solving for x from equations 1 and 2, and simplifying using equations 3 and 4 one gets

$$X = \frac{(s_1 - s_2) \cdot x_1 x_2}{s\,(x_2 - x_1) - s_2 x_2 + s_1 x_1} \qquad \text{Equ. 5}$$

During calibration the target is put at x_1 and x_2 respectively, and the positions s_1 and s_2 are detected. During range-finding operations, simply the position s of the laser spot on the detector is noted and equation 5 is used to compute range. This can be accomplished without knowing the baseline separation or angles between the detector and laser source.