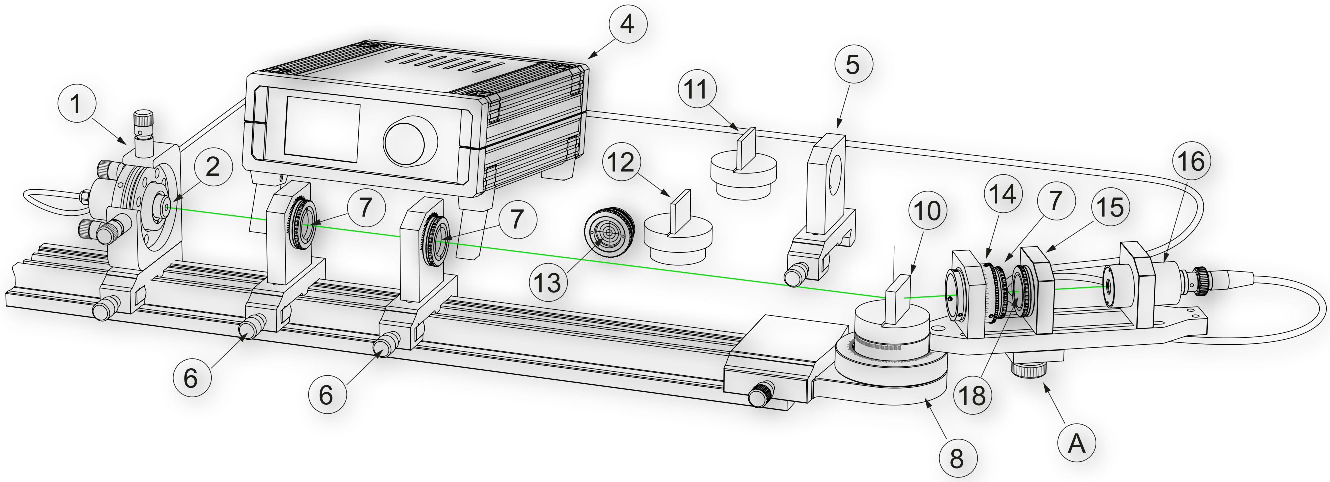
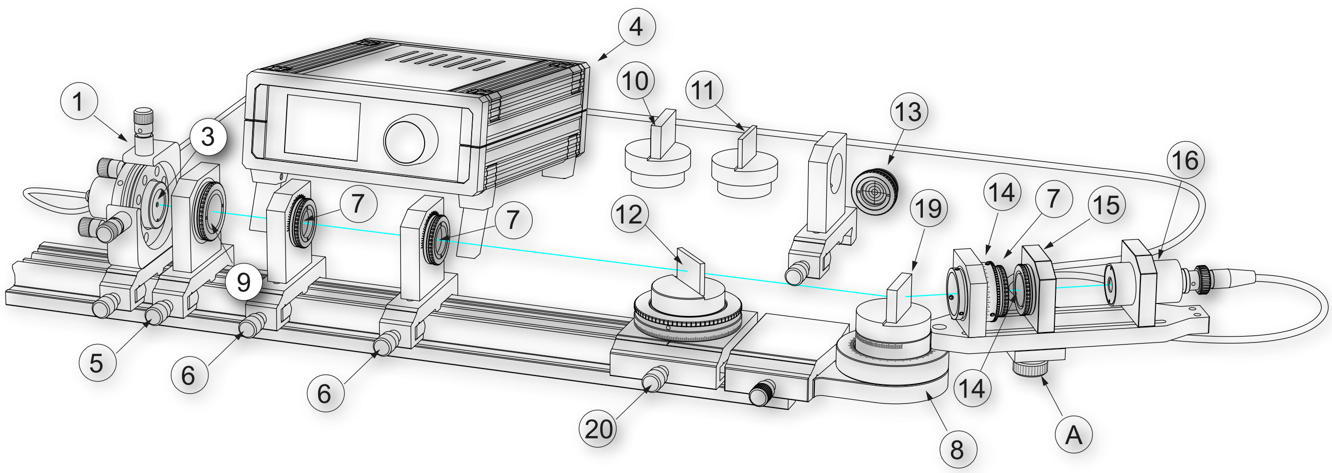
Photonik
Ingenieurbüro
Dr. Walter Luhs

UM-PE03 Manual for PE-0300 Reflection & Transmission





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1 Introduction

The fundamental law which describes the geometrical behaviour of light when passing from one medium to another is defined as the refraction law, stated by Willebrord Snell (Snellius) in the year 1621.

Fig. 1: Willebrord Snell (1580 - 1626) was a dutch scientist

At this point we will not stress the ancient geometrical optics as used by W. Snellius (1621) rather than using more modern ways of explanation. James Clerk Maxwell (1831 - 1879) and Heinrich Hertz (1857 - 1894) discovered that light shows the properties of electromagnetic waves and therefore can be treated with the theory of electromagnetism, especially with the famous Maxwell equations.

Heinrich Hertz
(1857 - 1894) German

James Clerk Maxwell
(1831 - 1879) Scotsman

1.1 The miracle of the light

Light, the giver of life, has always fascinated human beings. It is therefore natural that people have been trying to find out what light actually is, for a very long time. We can see it, feel its warmth on our skin but we cannot touch it.
The ancient Greek philosophers thought light was an extremely fine kind of dust, originating in a source and covering the bodies it reached. They were convinced that light was made up of particles.
As human knowledge progressed and we began to understand waves and radiation, it was proved that light did not, in fact, consist of particles but that it is an electromagnetic radiation with the same characteristics as radio waves. The only difference is the wavelength.
We now know, that the various characteristics of light are revealed to the observer depending on how he sets up his experiment. If the experimentalist sets up a demonstration apparatus for particles, he will be able to determine the characteristics of light particles. If the apparatus is the one used to show the characteristics of wavelengths, he will see light as a wave.

The question we would like to be answered is: What is light in actual fact? The duality of light can only be understood using modern quantum mechanics. Heisenberg showed, with his famous „Uncertainty relation“, that strictly speaking, it is not possible to determine the position x and the impulse p of a particle of any given event at the same time.

$$\Delta x \cdot \Delta p_x \geq \frac{1}{2}\hbar \qquad \textbf{(Eq 1.1)}$$

If, for example, the experimentalist chooses a set up to examine particle characteristics, he will have chosen a very small uncertainty of the impulse Δpx. The uncertainty Δx will therefore have to be very large and no information will be given on the location of the event.
Uncertainties are not given by the measuring apparatus, but are of a basic nature. This means that light always has the particular property the experimentalist wants to measure. We determine any characteristic of light as soon as we think of it. Fortunately the results are the same, whether we work with particles or wavelengths, thanks to Einstein and his famous formula:

$$E = m \cdot c^2 = h \cdot \nu \qquad \textbf{(Eq 1.2)}$$

This equation states that the product of the mass m of a particle with the square of its speed c corresponds to its energy E. It also corresponds to the product of Planck‘s constant h and its frequency ν, in this case the frequency of luminous radiation.

2 Optics and Maxwell’s Equations

It seems shooting with a cannon on sparrows if we now introduce Maxwell’s equation to derive the reflection and refraction laws. Actually we will not give the entire derivation rather than describe the way. The reason for this is to figure out that the disciplines Optics and Electronics have the same root namely the Maxwell’s equations. This is especially true if we are aware that the main job has been done by electrons but it will be done more and more by photons. Accordingly future telecommunication engineers or technicians will be faced with a new discipline the optoelectronics.

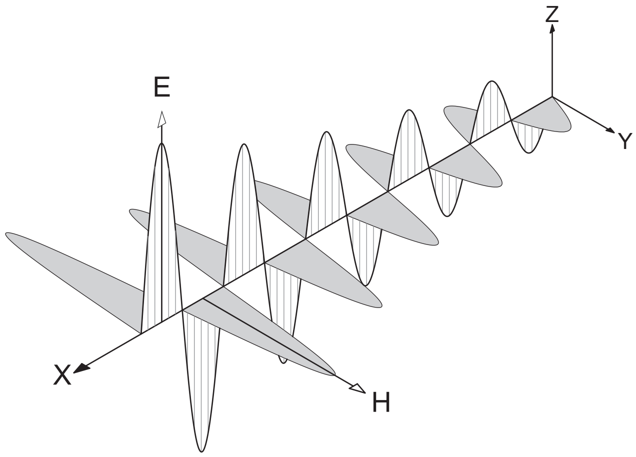


Fig. 2: Electromagnetic Wave

We consider now the problem of reflection and other optical phenomena as interaction with light and matter. The key to the description of optical phenomena are the set of the four Maxwell's equations as:

$$\nabla \times \vec{H} = \varepsilon \cdot \varepsilon_0 \cdot \frac{\partial \vec{E}}{\partial t} + \sigma \cdot \vec{E} \text{ and } \nabla \cdot \vec{H} = 0 \quad \textbf{(Eq 1.3)}$$

$$\nabla \times \vec{E} = -\mu \cdot \mu_0 \cdot \frac{\partial \vec{H}}{\partial t} \text{ and } \nabla \cdot \vec{E} = \frac{4\pi}{\varepsilon} \cdot \rho \quad \textbf{(Eq 1.4)}$$

ε_0 is the dielectric constant of the free space. It represents the ratio of unit charge (As) to unit field strength (V/m) and amounts to 8.859 1012 As/Vm.

ε represents the dielectric constant of matter. It characterises the degree of extension of an electric dipole acted on by an external electric field. The dielectric constant ε and the susceptibility χ are linked by the following relation:

$$\varepsilon = \frac{1}{\varepsilon_0} \cdot (\chi + \varepsilon_0) \quad \textbf{(Eq 1.5)}$$

$$\varepsilon \cdot \varepsilon_0 \cdot \vec{E} = \vec{D} \quad \textbf{(Eq 1.6)}$$

The expression (Eq 1.6) is therefore called „dielectric displacement" or simply displacement.

σ is the electric conductivity of matter.

The expression

$$\sigma \cdot \vec{E} = \vec{j}$$

represents the electric current density

μ_0 is the absolute permeability of free space. It gives the relation between the unit of an induced voltage (V) due to the presence of a magnetic field H of units in Am/s. It amounts to 1.256 106 Vs/Am.

μ is like ε a constant of the matter under consideration. It describes the degree of displacement of magnetic dipoles under the action of an external magnetic field. The product of permeability μ and magnetic field strength H is called magnetic induction.

ρ is the charge density. It is the source which generates electric fields. The operation ∇ or div provides the source strength and is a measure for the intensity of the generated electric field. The charge carrier is the electron which has the property of a monopole. On the contrary there are no magnetic monopoles but only dipoles. Therefore $\nabla \cdot \vec{H} = 0$ is always zero.

From (Eq 1.3) we recognise what we already know, namely that a curled magnetic field is generated by either a time varying electrical field or a flux of electrons, the principle of electric magnets. On the other hand we see from (Eq 1.4). that a curled electromagnetic field is generated if a time varying magnetic field is present, the principle of electrical generator.

Within the frame of further considerations we will use glass and air as matter in which the light propagates. Glass has no electric conductivity (e.g. σ =0), no free charge carriers (∇E=0) and no magnetic dipoles (μ = 1). Therefore the Maxwell equations adapted to our problem are as follows:

$$\nabla \times \vec{H} = \varepsilon \cdot \varepsilon_0 \cdot \frac{\partial \vec{E}}{\partial t} \text{ and } \nabla \cdot \vec{H} = 0 \quad \textbf{(Eq 1.7)}$$

$$\nabla \times \vec{E} = -\mu_0 \cdot \frac{\partial \vec{H}}{\partial t} \text{ and } \nabla \cdot \vec{E} = 0 \quad \textbf{(Eq 1.8)}$$

Using the above equations the goal of the following calculations will be to get an appropriate set of equations describing the propagation of light in glass or similar matter. After this step the boundary conditions will be introduced.

Let's do the first step first and eliminate the magnetic field strength *H* to get an equation which only contains the electric field strength *E*.

By forming the time derivation of (Eq 1.7) and executing the vector $\nabla\times$ operation on (Eq 1.8) and using the identity for the speed of light in vacuum:

$$c = \frac{1}{\sqrt{\varepsilon_0 \cdot \mu_0}}$$

we get:

$$\Delta\vec{E} - \frac{n^2}{c^2} \cdot \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad \textbf{(Eq 1.9)}$$

$$\Delta\vec{H} - \frac{n^2}{c^2} \cdot \frac{\partial^2 \vec{H}}{\partial t^2} = 0 \quad \textbf{(Eq 1.10)}$$

These are now the general equations to describe the interaction of light and matter in isotropic optical media as glass or similar matter. The Δ sign stands for the Laplace operator which only acts on spatial coordinates:

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

The first step of our considerations has been completed. Both equations contain a term which describes the spatial dependence (Laplace operator) and a term which contains the time dependence. They seem to be very „theoretical" but their practical value will soon become evident.

2.1 Light passing a boundary layer

Now we have to clarify how the wave equations will look like when the light wave hits a boundary. This situation is given whenever two media of different refractive index are in mutual contact. After having performed this step we will be in a position to derive all laws of optics from Maxwell's equations.

Let's return to the boundary problem. This can be solved in different ways. We will go the simple but safe way and request the validity of the law of energy conservation. This means that the energy which arrives per unit time at one side

of the boundary has to leave it at the other side in the same unit of time since there can not be any loss nor accumulation of energy at the boundary.
Till now we did not yet determine the energy of an electromagnetic field. This will be done next for an arbitrary medium. For this we have to modify Maxwell's equations (Eq 1.3) and (Eq 1.4) a little bit. The equations can be presented in two ways. They describe the state of the vacuum by introducing the electric field strength E and the magnetic field strength H. This description surely gives a sense whenever the light beam propagates within free space. The situation will be different when the light beam propagates in matter. In this case the properties of matter have to be respected. Contrary to vacuum, matter can have electric and magnetic properties. These are the current density j, the displacement D and the magnetic induction B.

$$\nabla\times\vec{\mathrm{H}}=\frac{\partial\vec{\mathrm{D}}}{\partial \mathrm{t}}+\vec{\mathrm{j}} \qquad \textbf{(Eq 1.11)}$$

$$\nabla\times\vec{\mathrm{E}}=-\frac{\partial\vec{\mathrm{B}}}{\partial \mathrm{t}} \qquad \textbf{(Eq 1.12)}$$

The entire energy of an electromagnetic field can of course be converted into thermal energy δW which has an equivalent amount of electrical energy:

$$\delta \mathrm{W}=\vec{\mathrm{j}}\cdot\vec{\mathrm{E}}$$

From (Eq 1.11) and (Eq 1.12) we want now to extract an expression for this equation. To do so we are using the vector identity:

$$\nabla\cdot(\vec{E}\times\vec{H})=\vec{H}\cdot(\nabla\times\vec{E})-\vec{E}\cdot(\nabla\times\vec{H})$$

and obtaining with (Eq 1.11) and (Eq 1.12) the result:

$$\delta W=-\nabla\cdot(\vec{E}\times\vec{H})-\frac{\partial}{\partial t}\left(\frac{\mu\mu_0}{2}\cdot\vec{H}^2+\frac{\varepsilon\cdot\varepsilon_0}{2}\cdot\vec{E}^2\right)$$

The content of the bracket of the second term we identify as electromagnetic energy Wm

$$W_{em}=\frac{1}{2}\mu\mu_0\cdot\vec{H}^2+\frac{1}{2}\varepsilon\varepsilon_0\cdot\vec{E}^2$$

and the content of the bracket of the first term

$$\vec{S}=\vec{E}\times\vec{H} \qquad \textbf{(Eq 1.13)}$$

(Eq 1.13) is known as Poynting vector and describes the energy flux of a propagating wave and is suited to establish the boundary condition because it is required that the energy flux in medium 1 flowing to the boundary is equal to the energy flux in medium 2 flowing away from the boundary. Let's choose as normal of incidence of the boundary the direction of the z-axis of the coordinate system. Than the following must be true:

$$\vec{S}_z^{(1)}=\vec{S}_z^{(2)}$$
$$(\vec{E}^{(1)}\times\vec{H}^{(1)})_z=(\vec{E}^{(2)}\times\vec{H}^{(2)})_z$$

By evaluation of the vector products we get:

$$E_x^{(1)}\cdot H_y^{(1)}-H_x^{(1)}\cdot E_y^{(1)}=E_x^{(2)}\cdot H_y^{(2)}-H_x^{(2)}\cdot E_y^{(2)}$$

Since the continuity of the energy flux must be assured for any type of electromagnetic field we have additionally:

$$E_x^{(1)}=E_x^{(2)} \qquad H_x^{(1)}=H_x^{(2)}$$
$$E_y^{(1)}=E_y^{(2)} \qquad H_y^{(1)}=H_y^{(2)}$$
$$or:$$
$$E_{tg}^{(1)}=E_{tg}^{(2)} \qquad H_{tg}^{(1)}=H_{tg}^{(2)}$$

(The index tg stands for "tangential")
This set of vector components can also be expressed in a more general way:

$$\nabla\times\vec{E}=\vec{N}\times(\vec{E}_2-\vec{E}_1)=0$$
$$\text{and} \qquad \textbf{(Eq 1.14)}$$
$$\nabla\times\vec{H}=0$$

$\vec{N}$ is the unit vector and is oriented vertical to the boundary surface. By substituting (Eq 1.14) into (Eq 1.11) or (Eq 1.12) it can be shown that the components of $\vec{B}=\mu\mu_0\cdot\vec{H}$ and $\vec{D}=\varepsilon\varepsilon_0\cdot\vec{E}$ in the direction of the normal are continuous, but $\vec{E}$ and $\vec{H}$ are discontinuous in the direction of the normal. Let's summarise the results regarding the behaviour of an electromagnetic field at a boundary:

$$E_{tg}^{(1)}=E_{tg}^{(2)} \qquad D_{norm}^{(1)}=D_{norm}^{(2)}$$
$$H_{tg}^{(1)}=H_{tg}^{(2)} \qquad B_{norm}^{(1)}=B_{norm}^{(2)}$$

By means of the equations (Eq 1.11), (Eq 1.12) and the above continuity conditions we are now in a position to describe any situation at a boundary. We will carry it out for the simple case of one infinitely spread boundary. This does not mean that we have to take an huge piece of glass, rather it is meant that the dimensions of the boundary area should be very large compared to the wavelength of the light. We are choosing for convenience the coordinates in such a way that the incident light wave (1) is lying within the zx plane (Fig. 3).

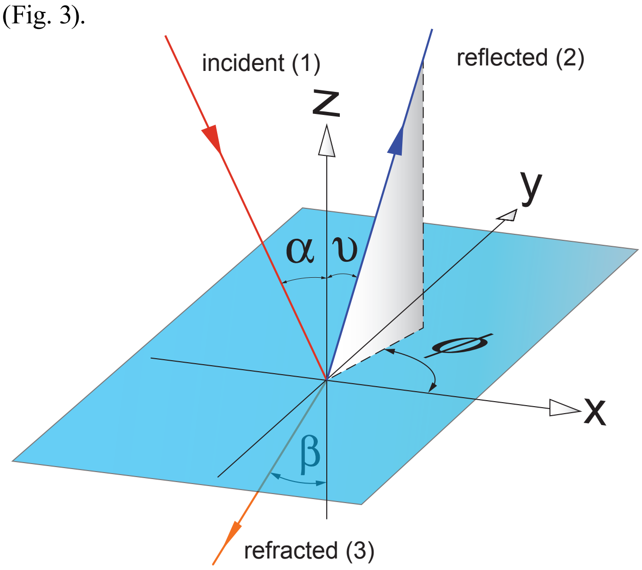


Fig. 3: Explanation of beam propagation

From our practical experience we know that two additional beams will be present. One reflected (2) and one refracted beam (3). At this point we only define the direction of beam (1) and choosing arbitrary variables for the remaining two. We are using our knowledge to write the common equation for a travelling waves as:

Theory

$$\vec{E}_1 = \vec{A}_1 \cdot e^{-i(\omega_1 \cdot t + \vec{k}_1 \cdot \vec{r}_1)}$$
$$\vec{E}_2 = \vec{A}_2 \cdot e^{-i(\omega_2 \cdot t + \vec{k}_2 \cdot \vec{r} + \delta_2)} \qquad \textbf{(Eq 1.15)}$$
$$\vec{E}_2 = \vec{A}_3 \cdot e^{-i(\omega_3 \cdot t + \vec{k}_3 \cdot \vec{r} + \delta_3)}$$

We recall that A stands for the amplitude, ω for the circular frequency and k represents the wave vector which points into the travelling direction of the wave. It may happen that due to the interaction with the boundary a phase shift δ with respect to the incoming wave may occur. Furthermore we will make use of the identity:

$$\vec{k} = \frac{2 \cdot \pi \cdot n}{\lambda} \cdot \vec{u} = \omega \cdot \frac{n}{c} \cdot \vec{u}$$

whereby n is the index of refraction, c the speed of light in vacuum, λ the wavelength, u is the unit vector pointing into the travelling direction of the wave and r is the position vector. Since we already used an angle to define the incident beam we should stay to use polar coordinates. The wave vectors for the three beams will look like:

$$\vec{k}_1 = n_1 \frac{\omega_1}{c} (\sin\alpha, 0, \cos\alpha)$$
$$\vec{k}_2 = n_1 \frac{\omega_2}{c} (\sin\upsilon \times \cos j_2, \sin\upsilon \times \sin j_2, -\cos\upsilon)$$
$$\vec{k}_3 = n_2 \frac{\omega_3}{c} (\sin\beta \times \cos j_3, \sin\beta \times \sin j_3, \cos\beta)$$

Rewriting (Eq 1.15) with the above values for the wave vectors results in:

$$\vec{E}_1 = \vec{A}_1 \cdot e^{-i\omega_1 \left(t + \frac{n_1}{c} \cdot (x \cdot \sin\alpha + z \cdot \cos\alpha)\right)}$$
$$\vec{E}_2 = \vec{A}_2 \cdot e^{-i\omega_2 \left(t + \frac{n_1}{c} \cdot (x \cdot \sin\upsilon \cdot \cos\phi_2 + y \cdot \sin\upsilon \cdot \sin\phi_2 - z \cdot \cos\upsilon)\right) + i\delta_2}$$
$$\vec{E}_3 = \vec{A}_3 \cdot e^{-i\omega_3 \left(t + \frac{n_2}{c} \cdot (x \cdot \sin\beta \cdot \cos\phi_3 + y \cdot \sin\beta \cdot \sin\phi_3 - z \cdot \cos\beta)\right) + i\delta_3}$$

(Eq 1.16)

2.2 Condition of continuity

Now it is time to fulfil the condition of continuity requiring that the x and *y* components of the electrical field E as well as of the magnetic field H are be equal at the boundary plane at *z=0* and for each moment.

$$E_1^x + E_2^x = E_3^x$$
$$E_1^y + E_2^y = E_3^y \qquad \textbf{(Eq 1.17)}$$
$$H_1^x + H_2^x = H_3^x$$
$$H_1^y + H_2^y = H_3^y$$

This is only possible if the all exponents of the set of equations (Eq 1.16) be equal delivering the relation:

$$\omega_1 = \omega_2 = \omega_3$$

Although it seems to be trivial, but the frequency of the light will not be changed by this process.

A next result says that the phase shift δ must be zero or π. Furthermore it is required that:

$$\phi_2 = \phi_3 = 0$$

and means that the reflected as well as the refracted beam are propagating in the same plane as the incident beam.

$$E_1^x = A_1^x \cdot e^{-i\omega \cdot \left(t + \frac{n_1}{c} \cdot (x \cdot \sin\alpha)\right)}$$
$$E_2^x = A_2^x \cdot e^{-i\omega \cdot \left(t + \frac{n_1}{c} \cdot (x \cdot \sin\upsilon)\right)}$$
$$E_3^x = A_3^x \cdot e^{-i\omega \cdot \left(t + \frac{n_2}{c} \cdot (x \cdot \sin\beta)\right)}$$

$$A_1^x \cdot e^{-i\omega \cdot \frac{n_1}{c} \cdot x \cdot \sin\alpha} + A_2^x \cdot e^{-i\omega \cdot \frac{n_1}{c} \cdot x \cdot \sin\upsilon} = A_3^x \cdot e^{-i\omega \cdot \frac{n_2}{c} \cdot x \cdot \sin\beta}$$

To obtain a real solution a further request is that:

$$\sin\alpha = \sin\upsilon \ \text{(Law of Reflection)}$$
$$\left(A_1^x + A_2^x\right) \cdot e^{-i\frac{\omega \cdot x}{c} \cdot n_1 \cdot \sin\alpha} = A_3^x \cdot e^{-i\frac{\omega \cdot x}{c} \cdot n_2 \cdot \sin\beta}$$

and further:

$$n_1 \cdot \sin\alpha = n_2 \sin\beta$$

or

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1} \qquad \textbf{(Eq 1.18)}$$

the well known law of refraction.
We could obtain these results even without actually solving the entire wave equation but rather applying the boundary condition.

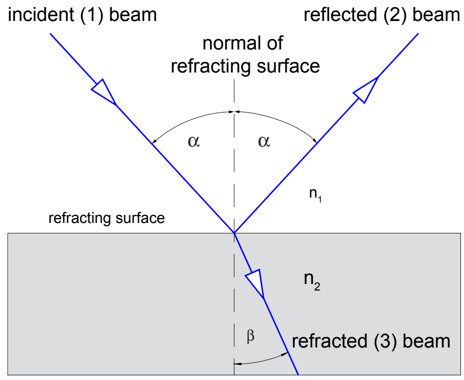


Fig. 4: Reflection and refraction of a light beam

Concededly it was a long way to obtain these simple results. But on the other hand we are now able to solve optical problems much more easier. This is especially true when we want to know the intensity of the reflected beam. For this case the traditional geometrical consideration will fail and one has to make use of the Maxwell's equations. The main phenomena exploited for the Abbe refractometer is the total reflection at a surface. Without celebrating the entire derivation by solving the wave equation we simply interpret the law of refraction. When we are in a situation where $n_1 > n_2$ it may happen that *sin(β)* is required to be *>1*. Since this violates mathematical rules it has been presumed that such a situation will not exist and instead of refraction the total

Theory

reflection will take place.

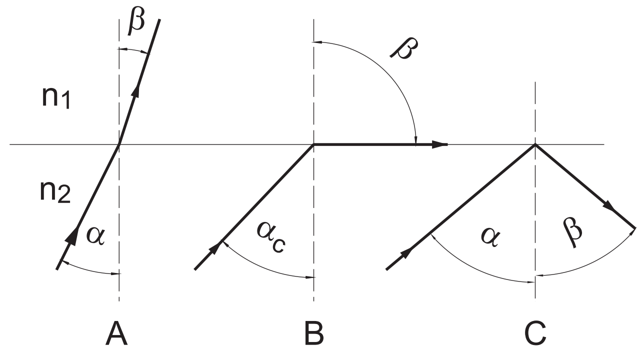


Fig. 5: From refraction to total reflection

The Fig. 5 above shows three different cases for the propagation of a light beam from a medium with index of refraction n_2 neighboured to a material with n_1 whereby $n_2 > n_1$. The case A shows the regular behaviour whereas in case B the incident angle reaches the critical value of:

$$\sin\beta = \frac{n_2}{n_1} \cdot \sin\alpha_c = 1 \qquad \textbf{(Eq 1.19)}$$

The example has been drawn assuming a transition between vacuum (or air) with $n_1 = 1$ and BK7 glass with $n_2 = 1.52$ (590 nm) yielding the critical value for $\alpha_c = 41.1°$. Case C shows the situation of total reflection when the value of $\alpha > \alpha_c$ and as we know from the law of reflection $\alpha = \beta$.

2.3 Fresnel's equation for Reflection and Refraction

So far we obtained information about the geometrical propagation of light at a boundary layer by applying the boundary conditions. In the next step we want to achieve information about the intensity of the reflected and refracted beam.

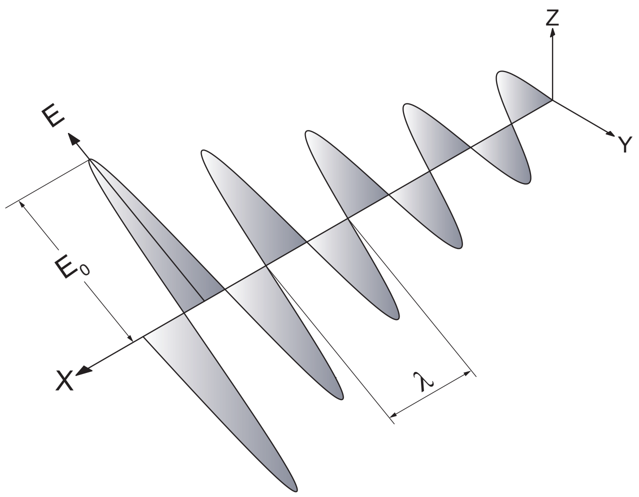


Fig. 6: Electrical field and polarisation

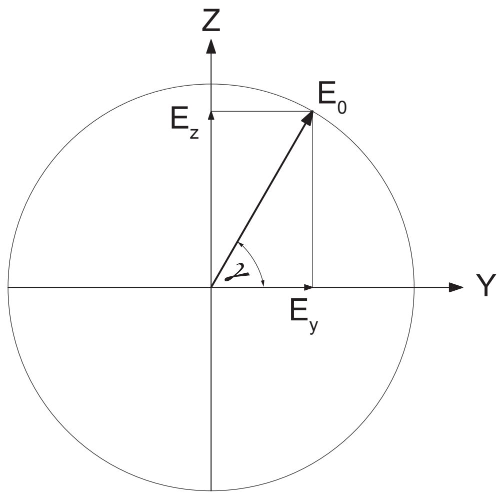


Fig. 7: Definition of the polarisation vector

Fig. 7 shows an example of a wave that is propagating in the X-direction and oscillating at the electrical field amplitude E_0 with an angle of γ to the Y-axis. The amplitude E_0 is can be described by its components, which oscillate in the Z- or Y-direction. If the angle γ is 90° then the wave oscillates in Z direction. In this case we term the wave as an "S - wave" for the opposite case when γ is 0° we talk about an "P - wave". In general the direction Z will be defined by the medium where the light wave is propagating. However, in call cases S and P waves are orthogonally polarised to each other.

Without demonstrating each step of the derivation we will discuss the results for the calculation of the intensity of the S and P components for the reflected and transmitted beam. By inserting the results into the condition of continuity and using (Eq 1.13) to obtain the intensity from the field amplitudes one gets

$$r_P = \frac{\tan^2(\alpha - \beta)}{\tan^2(\alpha + \beta)}$$

$$r_S = \frac{\sin^2(\alpha - \beta)}{\sin^2(\alpha + \beta)}$$

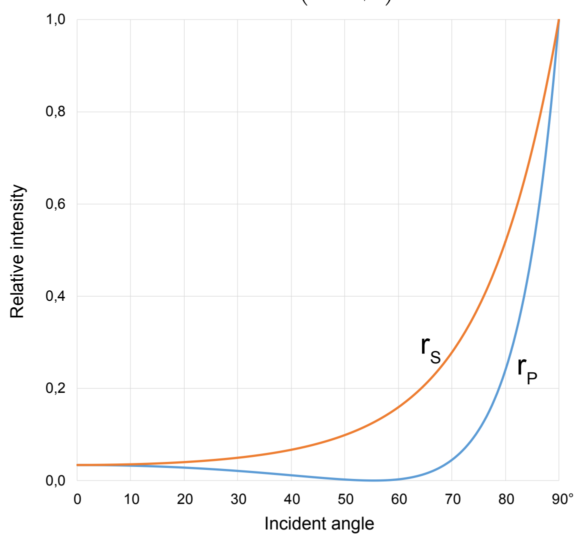


Fig. 8: Calculated values for r_P and r_S

Obviously the function for r_P exhibits a zero point which will be part of later experimental considerations since this is of high interest for applications without refection losses.

3 Description of the components

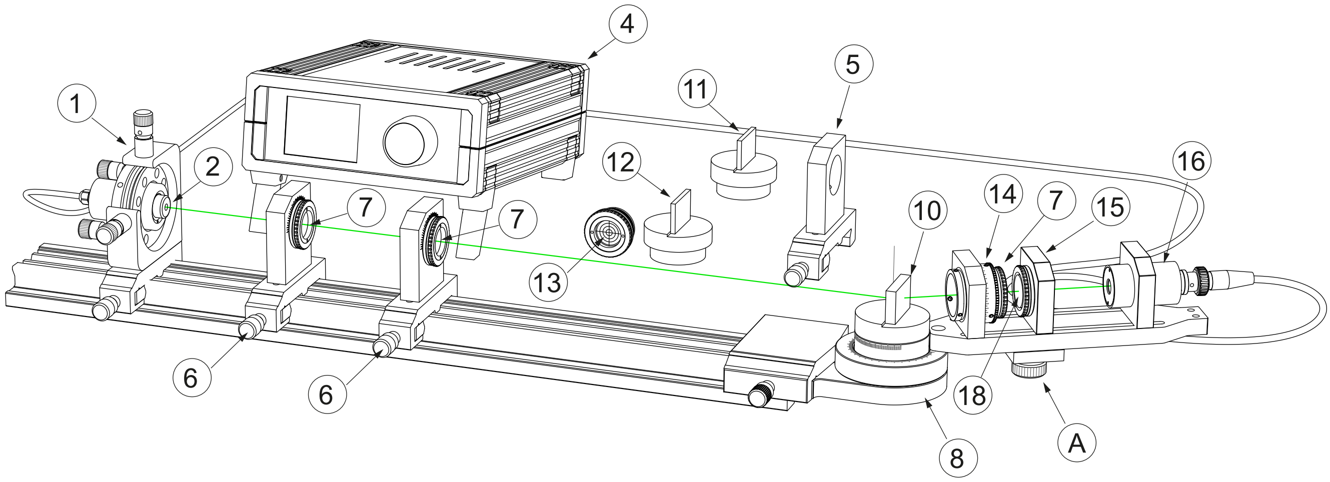


Fig. 9: Setup using the "green" Laser

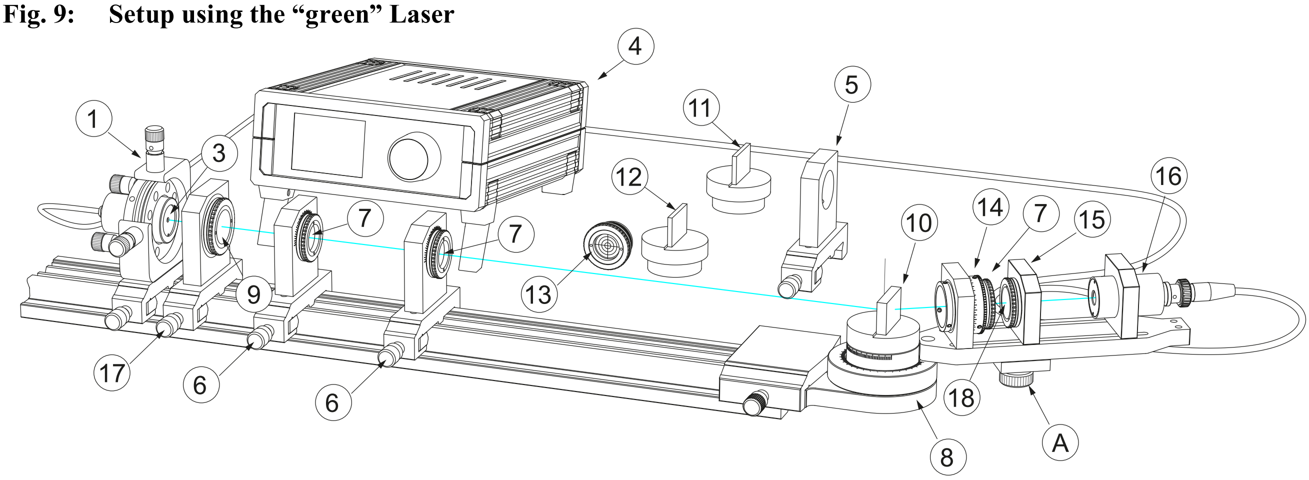


Fig. 10: Setup using the white light LED

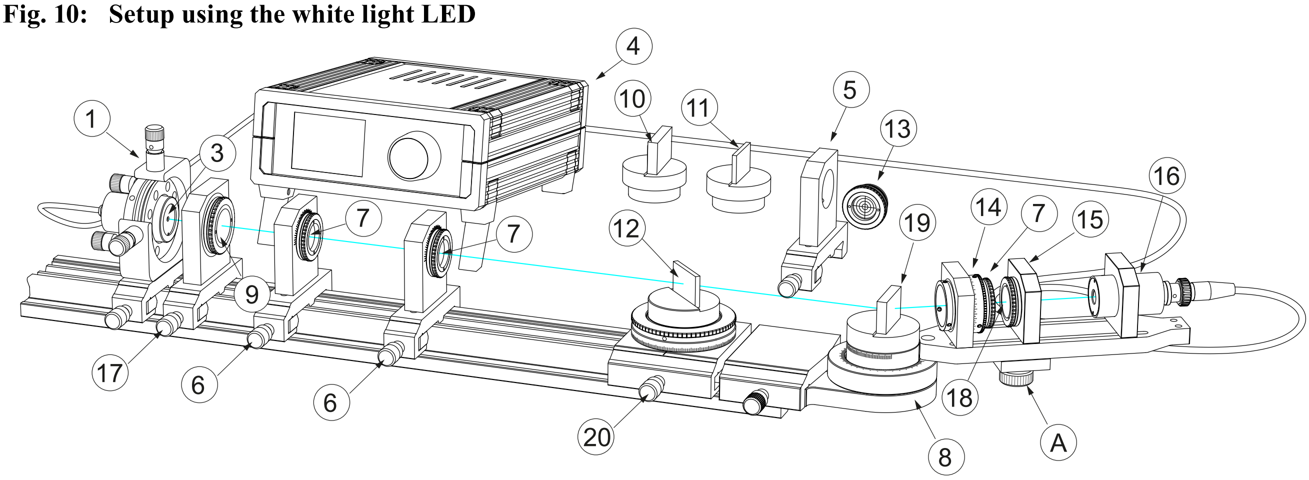


Fig. 11: Setup using rotator (20) for dichroitic mirror (12)

3.1 Optical Rail

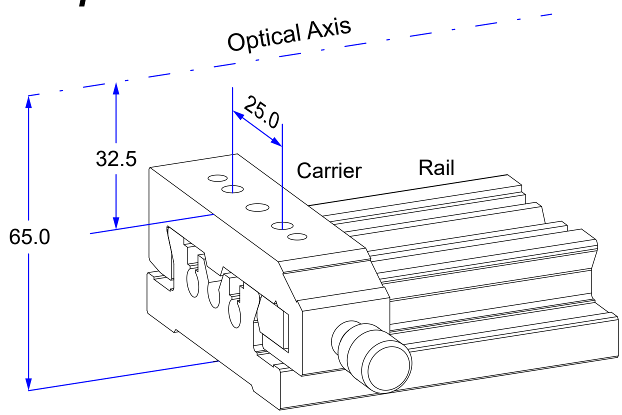


Fig. 12: Rail and carrier system (8)

The rail and carrier system provides a high degree of integral structural stiffness and accuracy. Due to this structure, it is a further development optimised for daily laboratory use. The optical height of the optical axis is chosen to be 65/105 mm above the table surface. The optical height of 32.5 mm above the carrier surface is compatible with all other systems like from MEOS, LUHS, MICOS, OWIS and LD Didactic. Consequently, a high degree of system compatibility is achieved.

3.2 Four axes adjustment holder

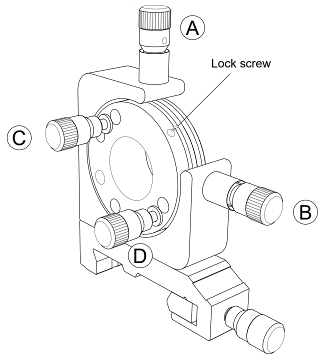


Fig. 13: Four axes adjustment holder (1)

This adjustment holder provides a free opening of 25 mm in diameter. All components like the optics holder and laser (2) as well as LED (3) light sources can be placed into it. A spring loaded ball keeps the component in position. By means of high precision fine pitch screws the inserted component can be tilted azimuthal and elevational (C and D) and shifted horizontally (B) and vertically (A). With the attached carrier this unit can be placed onto the provided rails. If needed the light source can be locked

3.3 White light LED

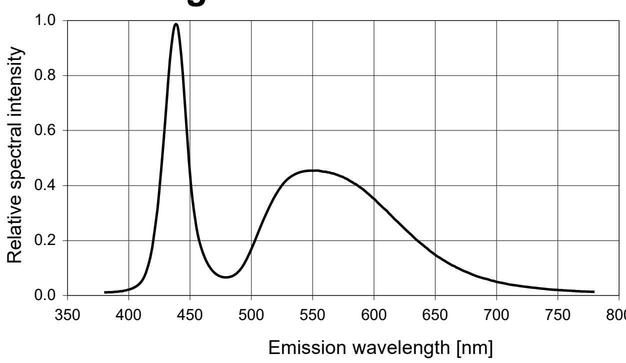


Fig. 14: White light LED (3)

The LED lamp emits the spectral composition of "white" light. The luminous flux amounts to 80 lumen. By means of the integrated lens the beam divergence is reduced to 12 degrees full angle. The housing has a diameter of 25 mm. By means of a 15 pin connector the LED is connected to the microprocessor controller (4).

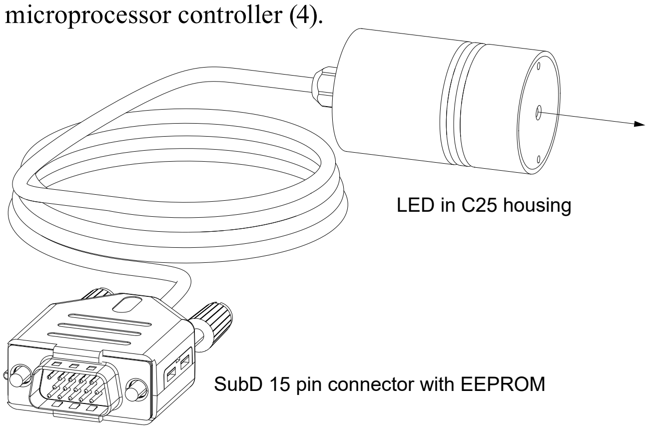


Fig. 15: White light LED (3)

3.4 Diode laser module

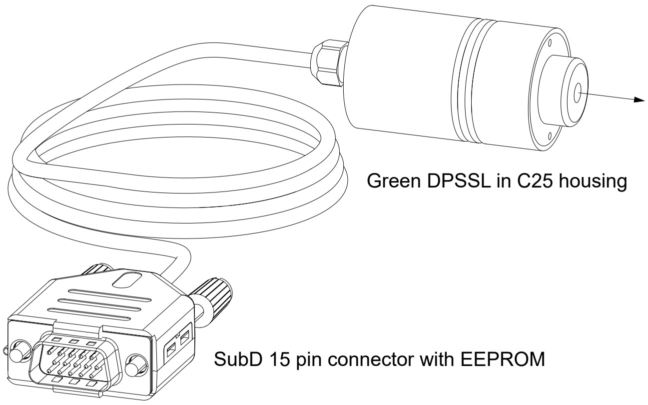


Fig. 16: Diode laser module (2)

The diode laser module DIMO 532 emits laser radiation with a wavelength of 532 nm and a maximum output power of 5 mw. Consequently laser safety regulations must be applied!

Laser class:	3R
Laser radiation:	<5 mw
Wavelength:	532 nm

3.5 Si-PIN Photodetector, BPX61

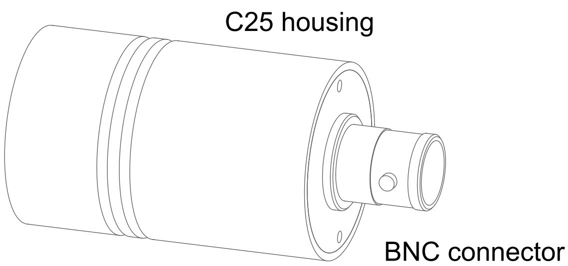


Fig. 17: Si-PIN Photodetector, BPX61 (16)

A Si PIN photodiode is integrated into a 25 mm housing with two click grooves. A BNC connector is attached to connect the module to the MK2 controller. The photodetector module is placed into the C25 mounting plate where it is kept in position by three spring loaded steel balls.

Experimental Setup

Parameter	Symbol	Value	Unit
Rise and fall time of the photo current at: R_L=50Ω; V_R=5 V; λ=850 nm and I_p=800 μA	t_r, t_f	20	ns
Capacitance at V_R = 0, f = 1 MHz	C0	72	pF
Wavelength of max. sensitivity	λ_{Smax}	850	nm
Spectral sensitivity S 10% of S_{max}	λ	1100	nm
Dimensions of radiant sensitive area	L × W	7	mm²
Spectral sensitivity, λ = 850 nm	S(λ)	0.62	A/W

Table 1: Parameter of the photodiode BPX61

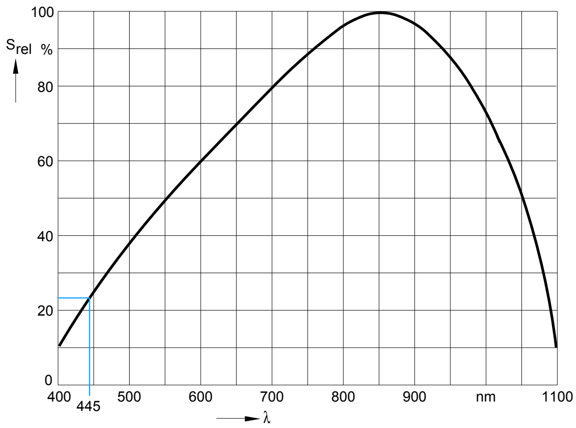


Fig. 18: Sensitivity curve of the BPX61 photodiode

The Mk2 controller contains a digital resistor and provides +5 VDC for the reverse voltage of the photodiode. They are connected to the BNC input (PDIN) as shown in the schematic of Fig. 19. At the output PDOUT of the signal box a signal is present which is given by the following equation:

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

I_c is the photocurrent 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 controllers 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(λ) [A/W], which depends on the wavelength of the incident light according to Fig. 18. From the Table 1 we take the value for S(850nm) 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 nm) from Fig. 18 (23% or 0.23).
The detected optical power P_{opt} in W is given as:

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

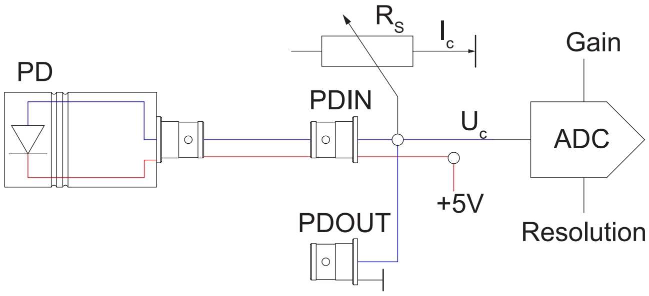


Fig. 19: Photodiode schematic

The photovoltage 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.

3.6 LED and Photodiode Controller

Fig. 20: LED and Photodiode Controller (4)

This microprocessor operated device contains an LED current 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 LED or photodiode. The controller reads the operation values of the connected LED or laser from the EEPROM located inside its connector. The device comes with a 230 VAC / 12 VDC wall plug power supply. The device can be controlled and the data read by an external computer via the USB bus.

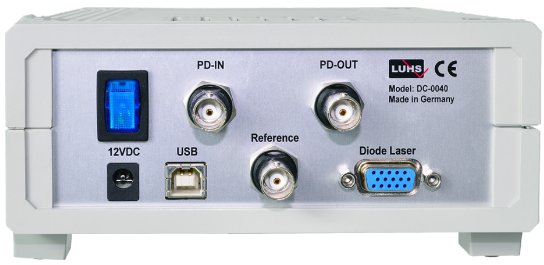
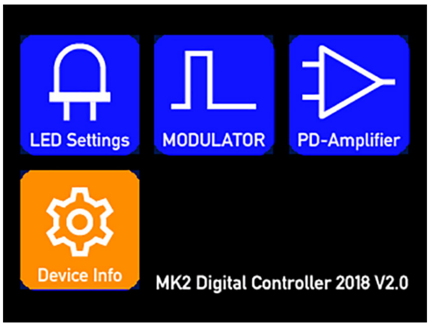


Fig. 21: The rear of the MK2 controller

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. The controller is operated by 12 VDC via the provided wall plug power supply.
The LED or laser are connected via the 15 pin SubD connector labelled "Diode Laser". When the LED or laser is operated in modulated mode, the reference modulator signal is available at the "MODULATOR" BNC connector.

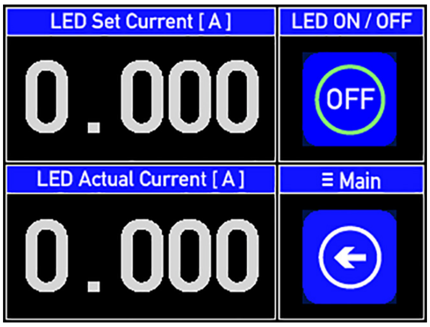
Experimental Setup

When the external 12 V is applied and switched on, the controller starts displaying the screen as shown in the figure above.

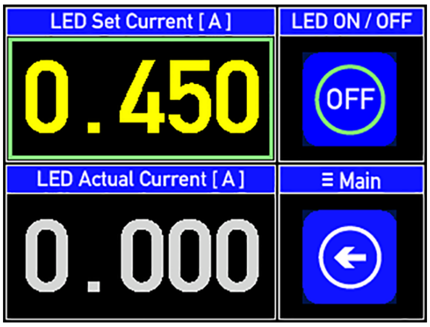


The upcoming interactive screen appears with the selection of 4 buttons:

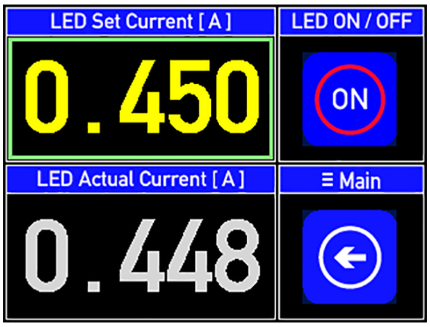
1. LED/Laser current settings
2. Modulation of the LED/laser
3. Photodiode Amplifier
4. Device and LED/laser information



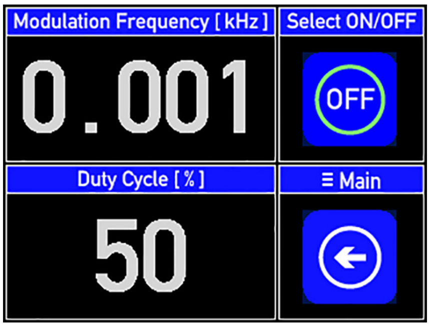
The current settings screen shows the set current as well as the actual current. With the LD ON/OFF touch button the laser is switched on or off. The Main touch button switches back to the main page.



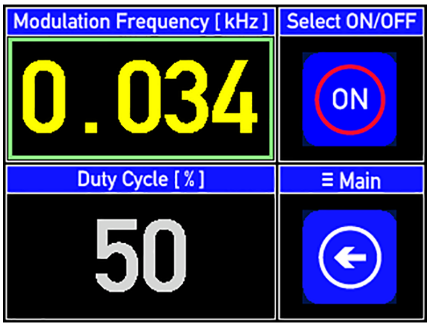
By touching the “LED Set Current” display field it is highlighted. By turning now the knob, the value of the injection current can be set and is immediately applied, provided the LED ON/OFF touch button is activated.



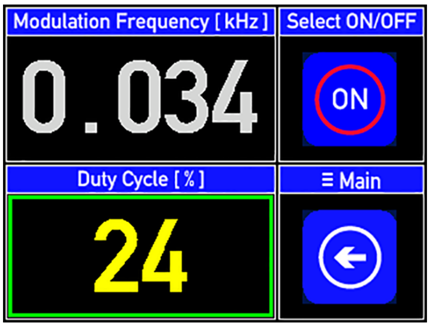
Touching the LED ON/OFF button switches the LED ON or OFF. When switched ON, the actual current is displayed in addition.



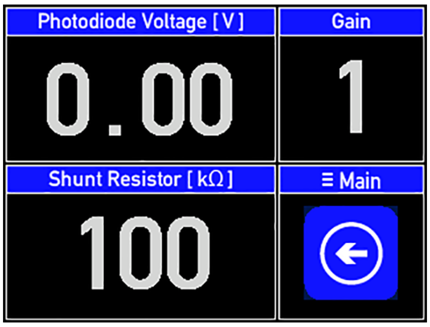
The LED or laser can be switched periodically on and off. This is for a couple of experiments of interest.



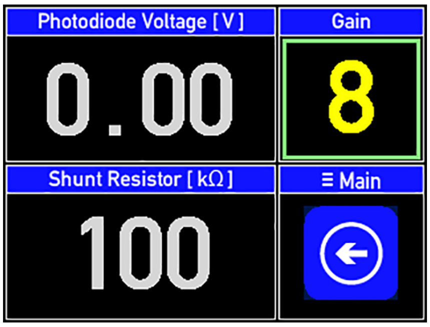
By tapping the display of the modulation frequency the entry is activated. Turning the settings knob will set the desired frequency value. The modulation becomes active, when the Modulator ON/OFF button is tapped.



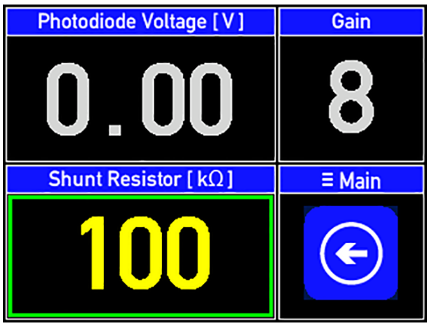
For some experiments it is important to keep the thermal load on the optically pumped object as low as possible or to simulate a flash lamp like pumping. For this reason the duty cycle of the injection current modulation can be changed in a range of 1...100 %. A duty cycle of 50% means that the OFF and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



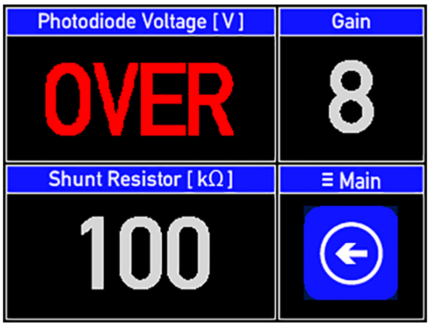
The photodiode page displays the measured photo voltage, the selected shunt resistor and the chosen gain.



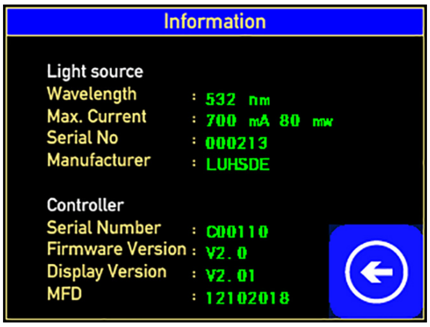
Tapping the gain display field, switches the gain from 1, 2, 4 and 8.



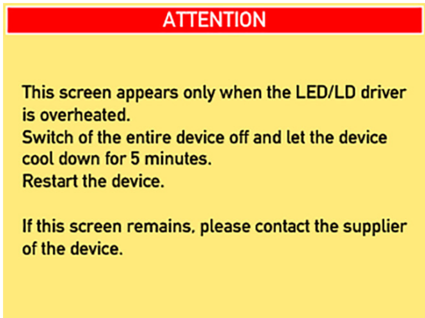
Activating the shunt resistor display field lets one set the shunt resistor by turning the digital knob. The value ranges from 1 kOhm to 200 kOhm.



If the photovoltage 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.



The diode laser module is connected via the 15 pin HD SubD jacket at the rear of the controller. The controller reads the EEPROM of the laser diode and sets the required parameter accordingly. This information and some more information about the controller are shown on this screen.



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

This screen appears only, when no LED or laser is connect to the device.

3.7 Mounting plate C25 on carrier

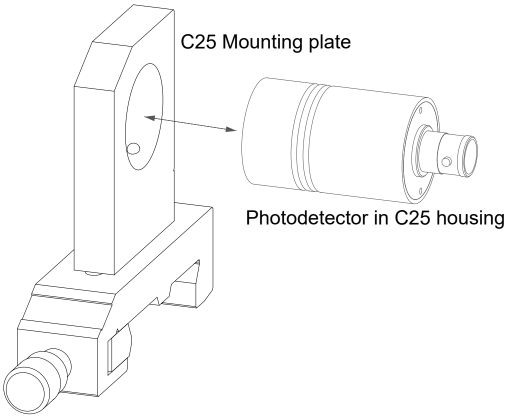


Fig. 22: Mounting plate C25 with carrier (5)

One of the key components are the mounting plates. From both sides elements with a diameter of 25 mm can be placed and fixed into the plate. Three spring loaded steel balls are clamping the C25 optics holder precisely in position. By means of the provided 20 mm carrier the mounting plate is attached to the optical rail.

3.8 Mounting plate C30 on carrier

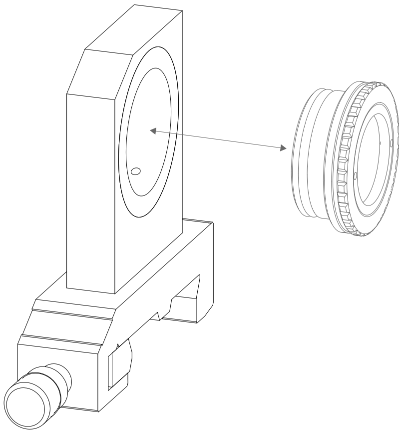


Fig. 23: Mounting plate C30 with carrier (17)

This frequently used component is ideal to accommodate parts with a diameter of 30 mm where it is kept in position by three spring loaded steel balls. Especially C30 mounts having a click groove are firmly pulled into the mounting plate due to the smart chosen geometry. The mounting plate is mounted to a 20 mm wide carrier.

3.9 Polarizer as well as analyzer

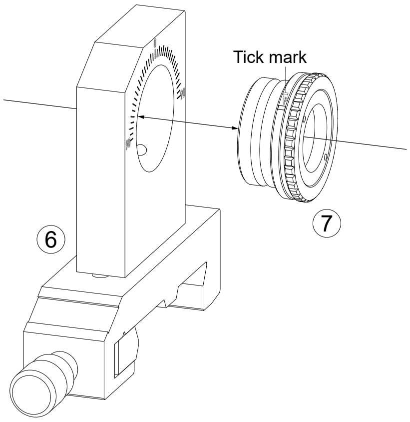
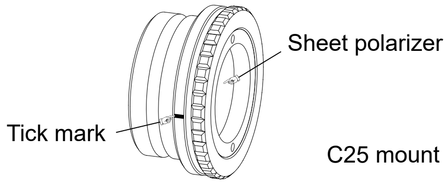


Fig. 24: Polariser as well as analyser (6 and 7)

The polarisation analyser has a mounting plate for C25 mounts and 180 degree scale with tick marks for each 5 degrees. It is attached to a 20 mm carrier. A C25 mount which is set into the Mounting plate is kept in position with three spring loaded steel balls are clamping the C25 optics holder precisely in position.

3.10 Polarizer in C25 mount



A film sheet polarizer is set into a C25 mount with a tick mark as vertical polarization indicator. The free opening is 16 mm.

3.11 Carrier with rotator

Fig. 25: Carrier with rotator (9)

On a hinged joined angle connector a mount with ±90° scale is provided. Into this mount the test objects are inserted. The swivel mount has a scale of ±150° and an arm to which various other components can be attached.

3.12 Coated glass plate on rotary disk

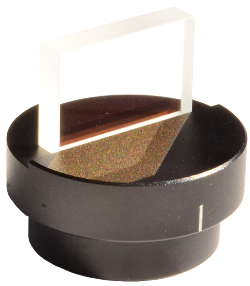


Fig. 26: Coated glass plate (10) on rotary disk

A glass plate 30 x 20 x 6 mm is coated with a broadband anti reflex (AR) layer. It is mounted to a rotary disc which can be placed in the triple swivel unit (9).

3.13 Mirrored glass plate (11) on ro-

tary disc

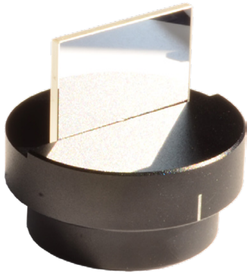


Fig. 27: Mirrored glass plate (11) on rotary disc

A glass plate of 20x30x2 mm by which one surface is coated with a high reflective metal like silver (Ag) or Aluminium (Al) is mounted onto a rotary disc which can be placed into the triple swivel unit (9).

3.14 Dichroic mirror on rotary disc

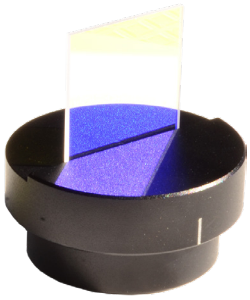


Fig. 28: Dichroic mirror on rotary disc (12)

A dichroitic beam splitter plate is mounted on a rotary disc which can be placed into the triple swivel unit (9). The plate is coated in such a way that for an incident angle of 45° the wavelength of 530 nm is reflected and the wavelength of 630 nm transmitted.

3.15 Crossed hair target

Fig. 29: Crossed hair target (13)

A crossed hair target is set in a 25 mm click mount which can be inserted into the mounting plate on a carrier 20 mm. This unit serves for the alignment of a light beam with respect to the optical axis of the setup.

3.16 Polarization analyzer

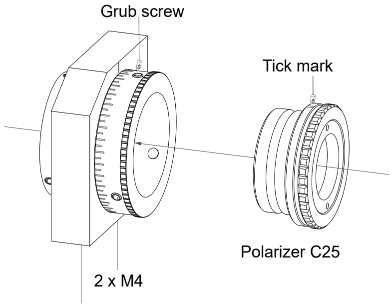


Fig. 30: Polarisation analyser(14)

In a rotational ring mount with a 360°, scale a polarizer is assembled. In case the incident light is polarized, a minimum intensity occurs indicating that the polarizer is adjusted 90° with respect to the polarization direction of the incident light. The rotator has a scale gradation from 0 - 360° at intervals of 5°. The unit is made out of special anodized aluminium and can be directly attached to the swivel unit (9) with 2 M4 screws. A high quality acrylic sheet polarizer is contained in a C25 optics mount. A C25 mount which is set into the rotary stage and is kept in position with three M2.5 grub screws. The module comes with a fitting Allen key.

3.17 Mounting plate C25-40

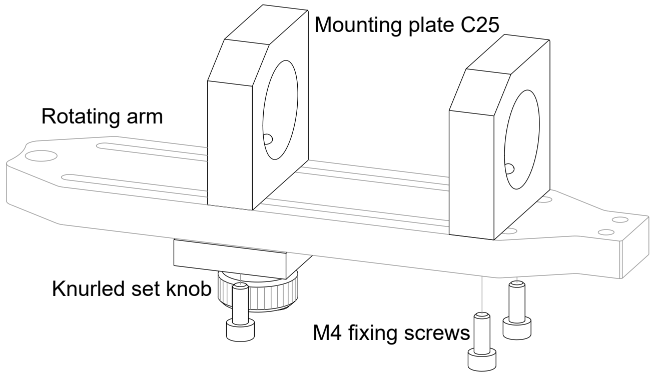


Fig. 31: Mounting plate C25 (15)

One of the key components are the mounting plates. From both sides elements with a diameter of 25 mm can be placed and fixed into the plate. Three spring loaded steel balls are clamping the C25 optics holder precisely in position. One of the mounting plate is fixed with a glider to the rotating arm and accommodates the focusing lens (18). With the knurled set knob the plate is fixed after the desired position has been found. The right plate accommodates the photodetector (16) and is fixed in its position.

3.18 Focussing lens

Fig. 32: Focussing lens (18)

A plano-convex lens having a focal length of 60 mm is mounted into a lens holder C25. The holder can be placed into the mounting plate (15) which provides in combination with the spring loaded balls of the mounting plate a soft snap-in. To collimate the emission of the white LED (3) an achromate with a focal length of 40 mm is used (9), however, this lens is mounted into a C30 lens holder and fits into the mounting plate C30.

3.19 Grating on rotary holder

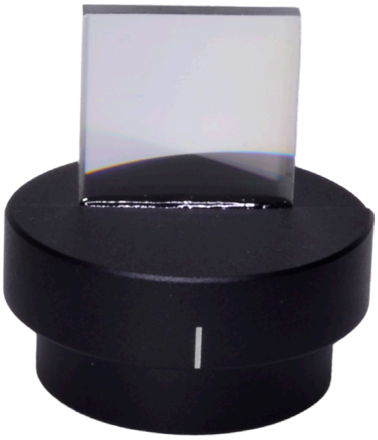


Fig. 33: Grating (19) 600 lines/mm on rotary holder

A holographic grating (1) is protected between two glass plates mounted in a regular slide holder. The resolution is 600 lines per mm. The grating is attached to a rotary disk

3.20 Swivel holder with scale

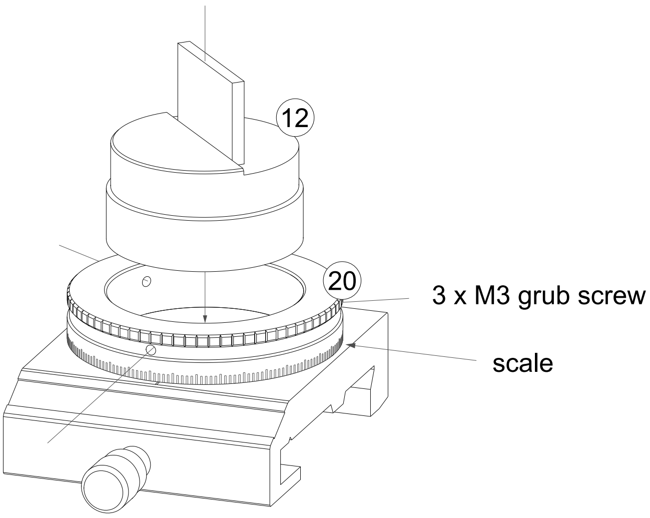


Fig. 34: Swivel holder with scale (20)

Into a carrier (20) with 65 mm width a swivel holder is integrated. Components to be rotated are inserted (12) and their angular position can be determined by the scale (C) in steps of 2 degrees.

Measurements

4 Measurements

4.1 Preliminary alignment steps

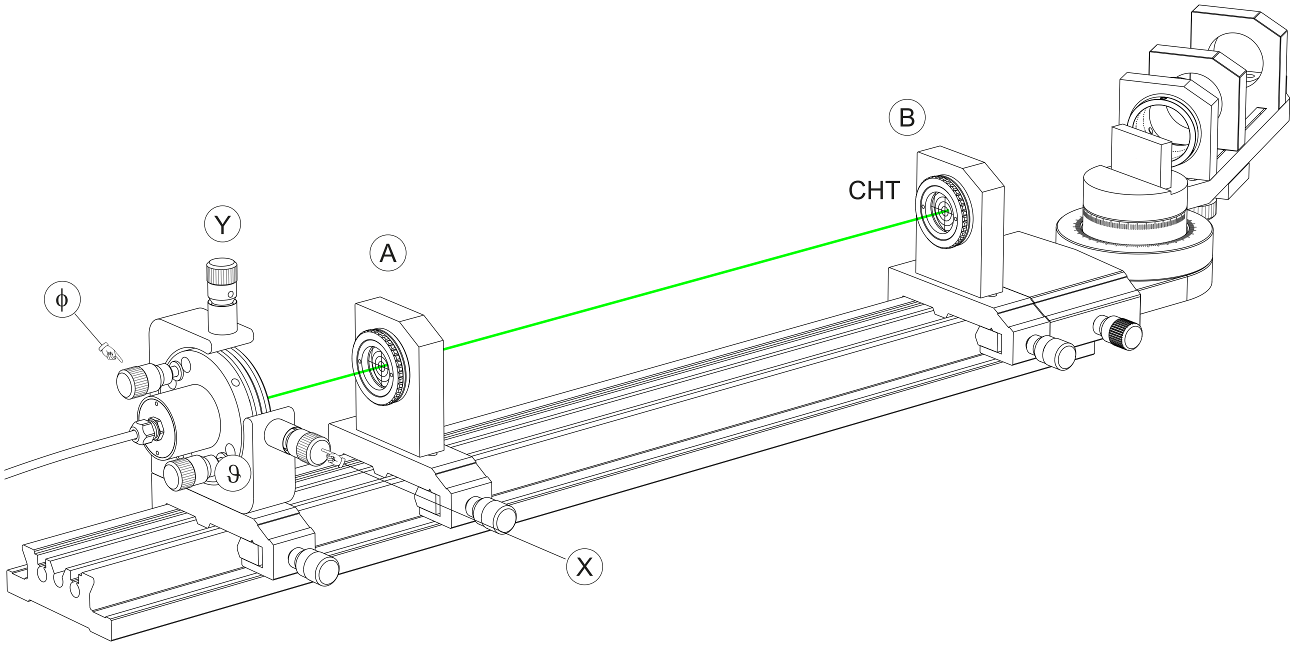


Fig. 35: Centring the laser beam to the crossed hair target (CHT)

The Fig. 35 shows the CHT in the far position (B). The beam is aligned by means of the ϑ or φ adjusters to the centre of the CHT. Subsequently the CHT is moved close to the laser (position A) and the beam is now aligned by using the X and Y adjuster. Maybe the steps has to be repeated two to three times.

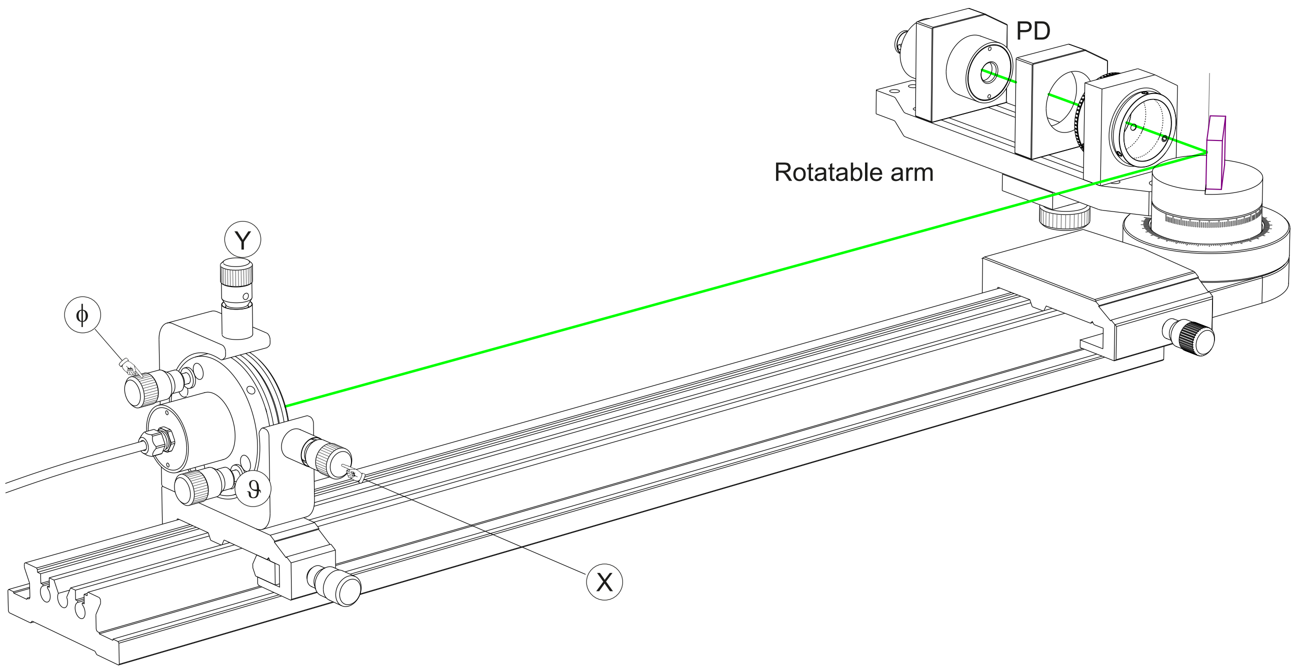


Fig. 36: Fine adjustment including the test object

In the second step the optical component under test is set into the holder of the rotatable arm. Both the component as well as the rotatable arm can be rotated independent from each other. For all angular positions of the optical components the laser beam shall hit the centre of the photodetector (PD) which is turned into the desired position. If not, the laser adjustment holder needs to be realigned.

4.2 Law of reflection

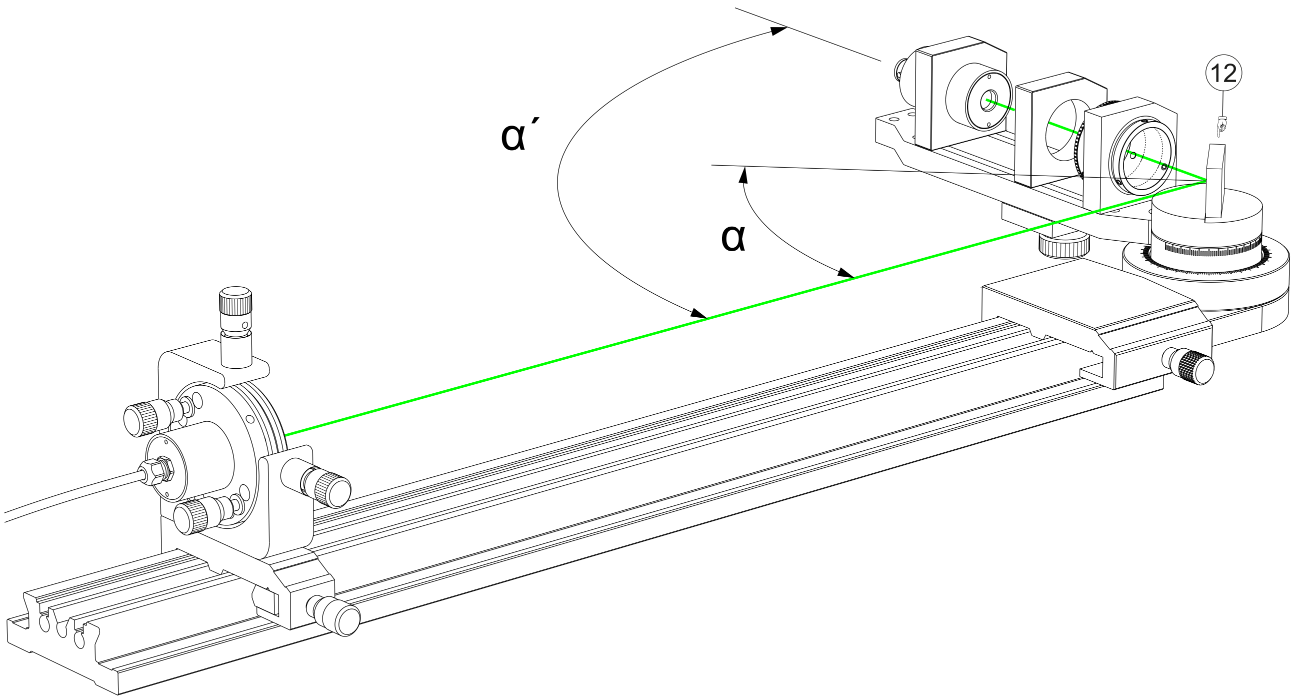


Fig. 37: Setup to measure the law of reflection

The optical component (12) is placed into the holder of the swivel unit and set to the desired angular position. The rotatable arm is rotated in such a way that the reflected beams fully hits the photodetector. The angular position is measured. Depending on the task, this procedure is repeated for each 2° of the optical component. The graphical presentation should show a linear function with a defined slope.

4.3 Law of refraction

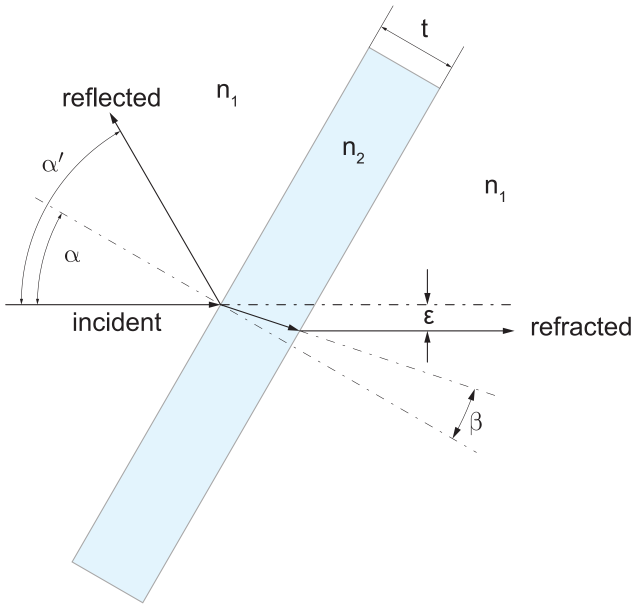


Fig. 38: Beam propagation through a tilted thick plate

The Fig. 38 suggests that the law of refraction cannot be verified directly by using a thick glass plate. Only the parallel beam offset ε can be measured for a set of given angular position. For this purpose the laser beam without an optical component is guided to a fixed screen (wall) and the spot is marked. After inserting the component the beam deviation ε is measured as function of the incident angle α. The equation giving $\varepsilon=f(\alpha, n_1, n_2, t)$ is derived by using Fig. 38 and compared with the measured values.

Measurements

4.4 Fresnel's law of reflection

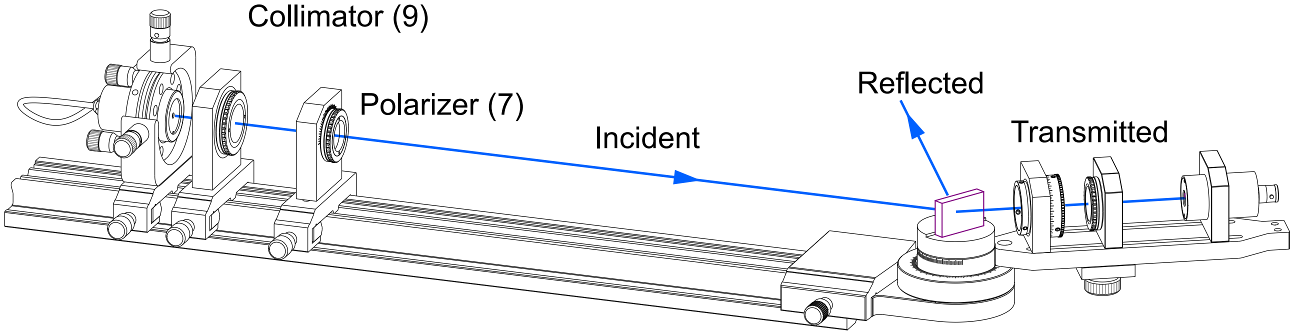


Fig. 39: Setup to verify the Fresnel's law

Instead of the green laser the white light LED is used within the next series of experiments. By means of the collimator a more or less parallel beam is created by moving the collimator forth and back until a crisp shaded round beam appears. The white light is in fact a spectral superposition of discrete emission bands (see Fig. 14). To check the polarization of this light we place the polarizer in front of it. The intensity will not change significantly when rotating the polarizer which indicates that the white light has no preferred direction of polarization. Using the second polarizer we can demonstrate that the light passed the first polarizer is now polarized. After removing the second polarizer the measurements starts. Measurements are taken for 0° and 90° of polarization for a set of angular positions of the glass plate resulting in a graph as shown as example of Fig. 40.

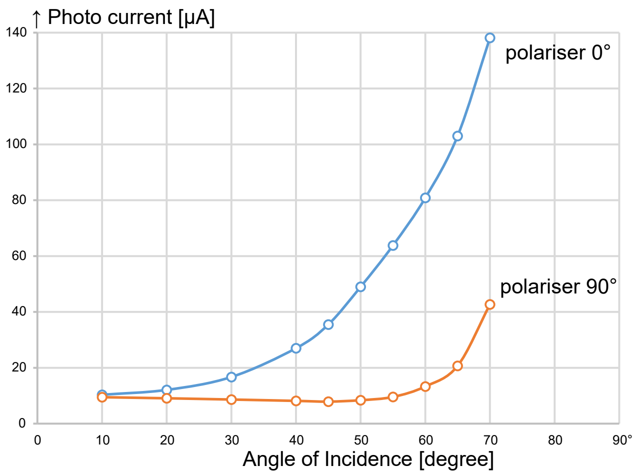


Fig. 40: Reflected intensity versus incident angle

I can be noticed that for the curve with 90° polarization the curve goes through a minimum. The location of the minimum is also termed as Brewster's angle. Drawing the results only for this values in a separate graph (Fig. 41) this minimum becomes more clear. To find a better minimum, the steps can be selected down to 2° instead of 5° as shown.

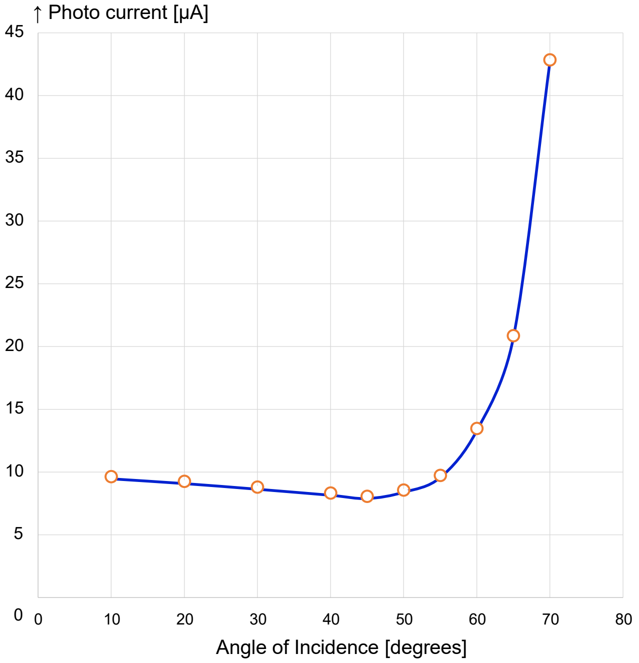


Fig. 41: Showing only reflected light with 90° incident polarisation

Measurements

4.5 Reflection and Polarisation

4.5.1 Polarization by reflection

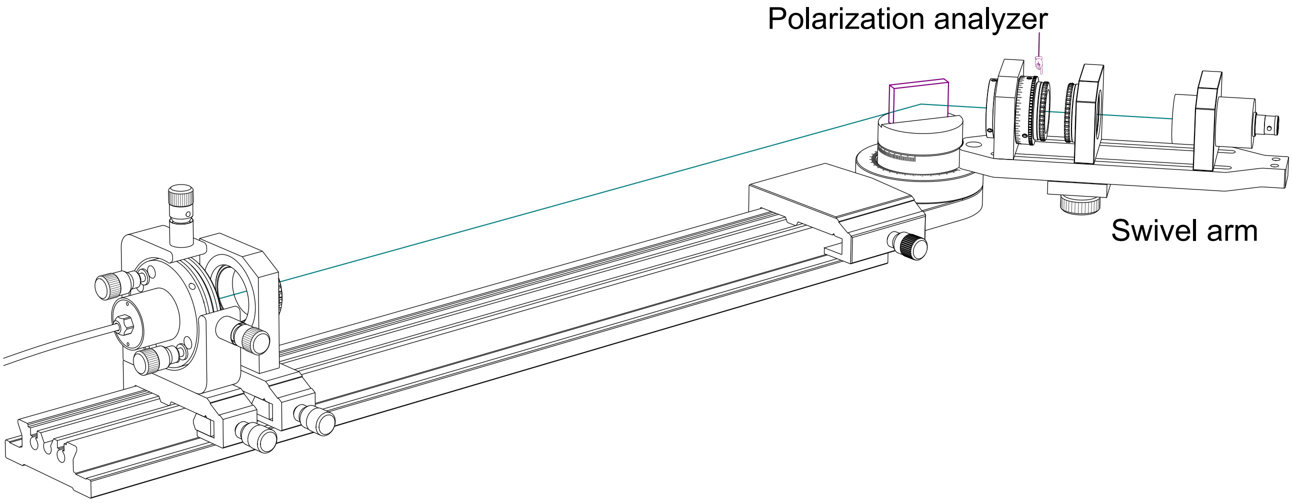


Fig. 42: Setup to demonstrate polarisation by reflection

In the setup of Fig. 42 the polarizer in front of the white light LED has been removed so that non-polarized light will be used. The swivel arm is rotated to the angle for which we measured the minimum of reflection. We place the polarization analyzer in front of the focusing lens of the photodetector and are measuring the polarization state of the reflected light.

4.5.2 Dichroitic mirror

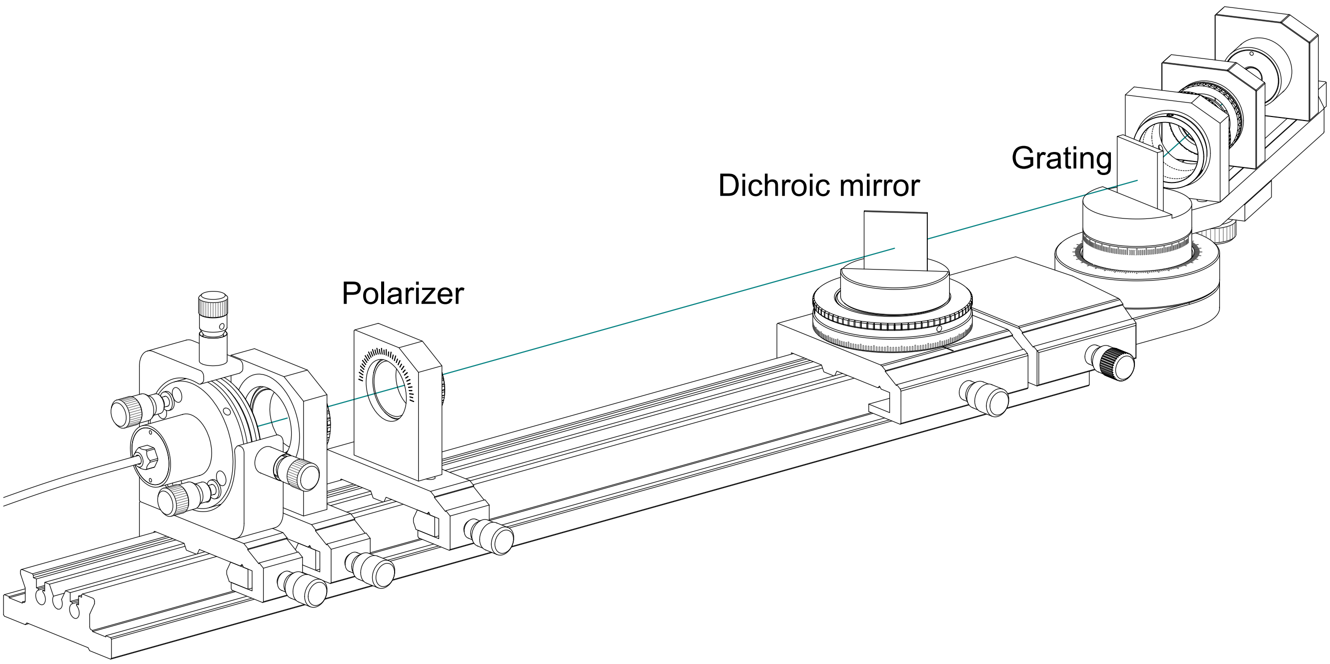


Fig. 43: Setup to demonstrate the angular dependance of spectral reflectivity.

The dichroitic mirror is set into the swivel holder with scale (20). The transmitted light passes the grating and creates spectral distributions of multiple orders which can be monitored on a piece of paper. The swivel arm can be rotated to a spectral region of interest, for instance blue and the transmitted light is measured for various angles of the dichroitic mirror.

4.6 Measurement of the Light Source

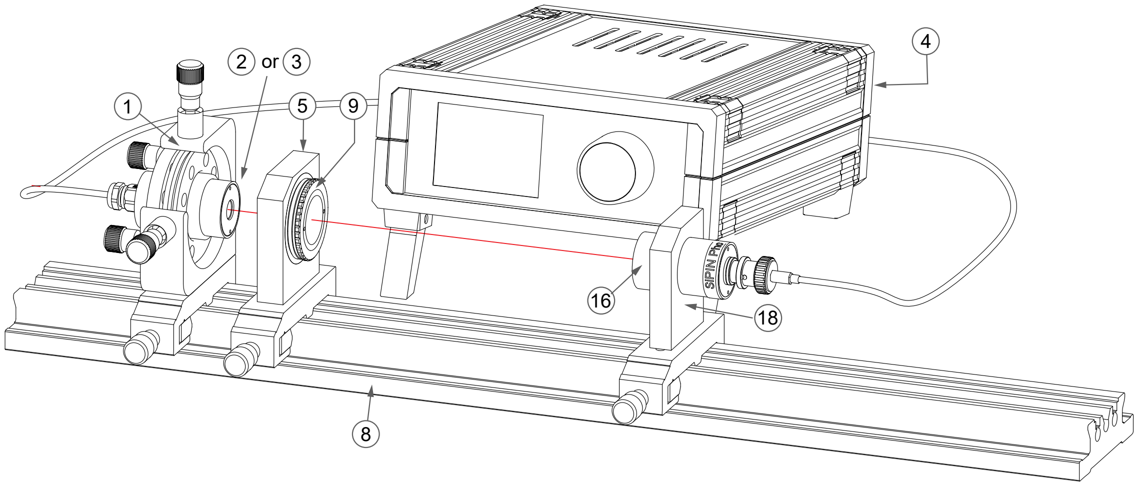


Fig. 44: Setup to measure the optical output power versus the injection current of the LED or DPSSL

As light source either the white LED (2) or the "green" laser (3) is used. The light source is clicked into the four axes kinematic mount (1) and connected to the LED and photodiode controller (4). Each light source has an embedded non-volatile memory into which the property of the light source is stored. The information is processed and displayed by the controller (4) to ensure the operation of the attached light source within its allowed parameter. In addition, the controller contains a pre-amplifier and processing stage for the attached photodiode. The settings are selected by means of the touch screen and set by the precision digital settings knob. The measurements starts with the characterization of the light source as intensity versus injection current and versus the analyzer (6+7) angle to check the polarization of the selected light source.

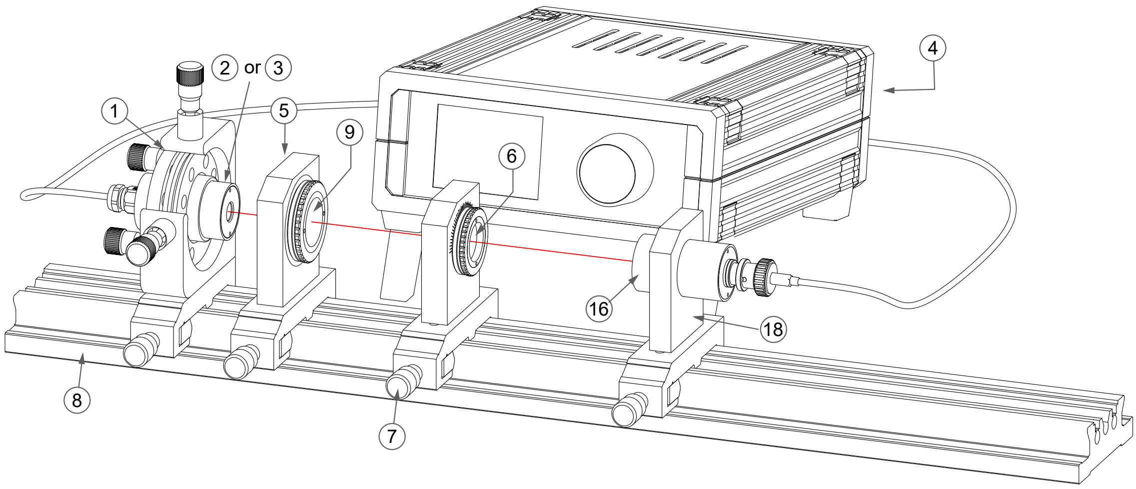


Fig. 45: Setup to measure the polarization of the selected light source

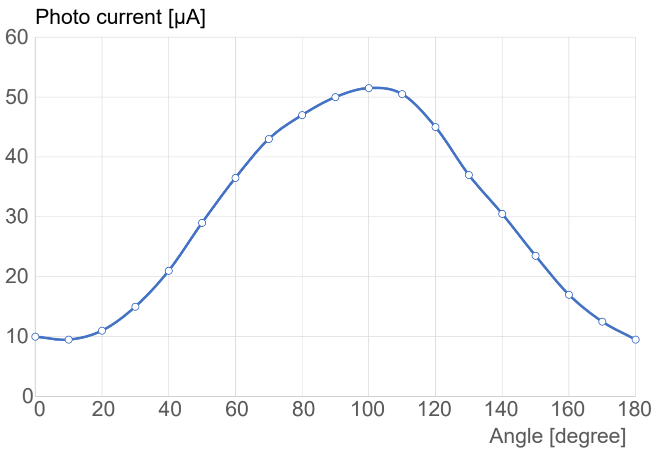
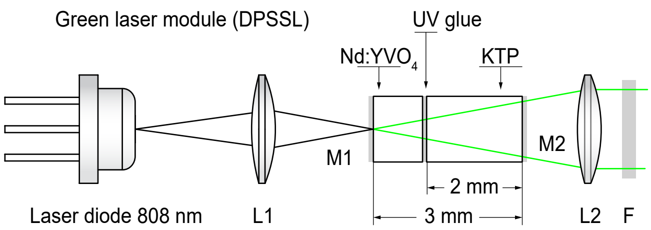


Fig. 46: Polarization of the green DPSSL

Notes for the green DPSSL:

The KTP cystal generates green emission in both directions. However, the back direction is reflected at the Mirror M1 to enhance the output power. Two beams are leaving collinear the DPSSL with a phase shift to one another. Depending on the thermal length of the crystal compound the phase shift varies resulting in different polarization states of the green emission. It is recommended to let the DPSSL warm up for 10 minutes before the measurement starts.



Measurements

4.7 Malus' Law and Optical Power Control

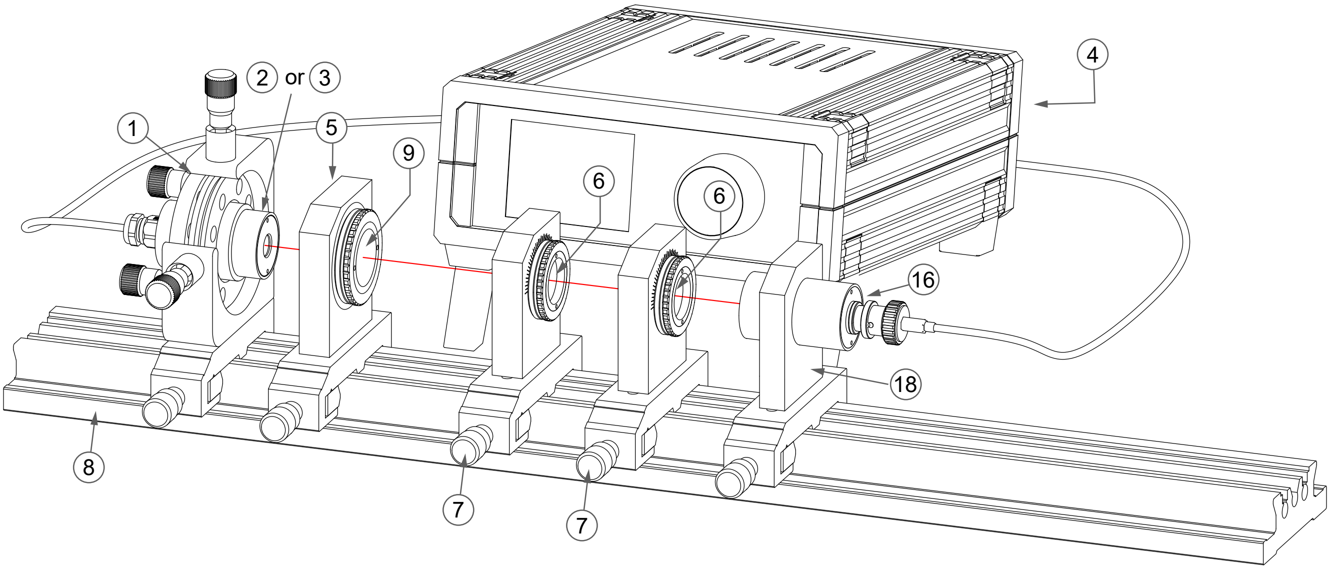


Fig. 47: Setup to verify Malus' law

The achromat (9) is used to collimate the radiation of the LED to obtain an almost parallel light beam. To make sure that the light is linearly polarized, the first polarizer (6+7) is placed behind the collimator (9) and turned to maximum intensity. The second polarizer (6+7) is used as analyzer. The transmitted intensity is measured with the photodetector (16) and the controller (4). An angular plot of the intensity yields the verification of the Malus' law. Such an arrangement is often used to control the intensity of a light source when the change of the emission wavelength by the control of the injection current is not desired.

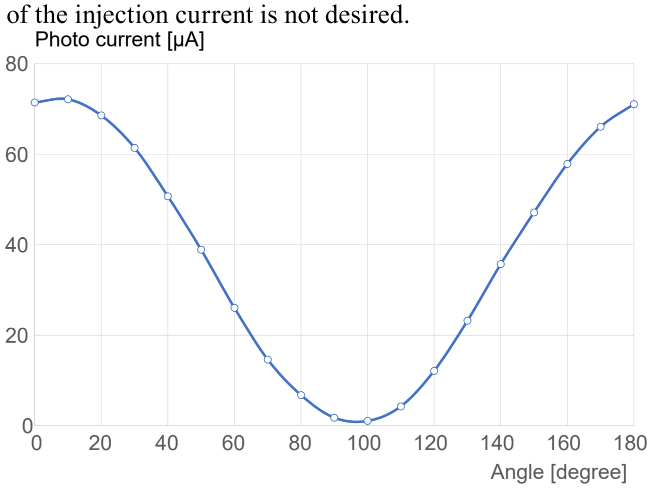


Fig. 48: White LED at 434 mA, gain 1 and shunt resistor 28 k.

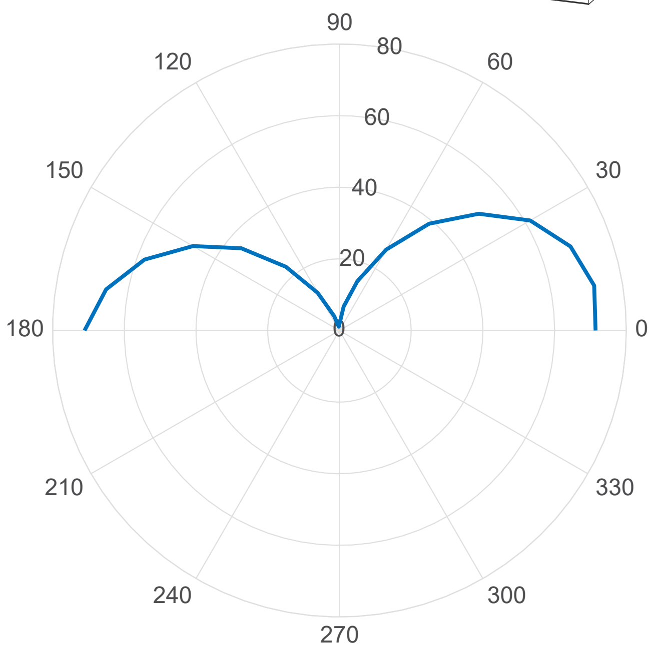


Fig. 49: Same values as Fig. 49, however drawn in polar coordinates