Manual
UM-07 Laser Safety

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1 Introduction

In this experiment the students are encouraged to convert the essential theoretical contents regarding "Laser Safety" into practice. The application and use of the basics in calculation defined within the standards is submitted and trained by means of practical examples. The major measurement task is to determine the intensity of a laser beam which is defined as power per cross section typically given in W/m². The power is measured by using a calibrated power meter. The cross section and the divergence are determined by a set of imaging lenses with known focal lengths. In addition to the direct exposure also the danger of scattered light is classified by using a scatter probe mounted on a pivot arm. The experiment is divided into several segments. Aspects such as the following ones have been considered:

1. Determination of the maximum permissible radiation (MPR) for skin and eyes
2. Minimum safety distance from a radiation source for direct and indirect irradiation of the skin and the eyes, (MSD)
3. Characterization of a pulsed laser system
4. Requirements for laser safety goggles, transmission of optical filter

The fundamentals of IEC 60825 or ANSI Z136 or corresponding literature of laser safety should be known. The danger of lasers is understood by the characteristic properties of the laser radiation. In comparison with other light sources, a high energy and power density can be attained, because of the generally small beam divergence the radiation density can be exceedingly high even at large distances from the laser (potential danger of lasers used in metrology). Not only the direct radiation also reflected and scattered radiation can cause damage at a large distance from the radiation source. Laser radiation can be generated within a broad spectral range. It extends from a few nanometers up to some hundred micrometers and is, in many cases, outside of the visible spectrum. The damage of the biological tissue (skin, eye) depends strongly on the wavelength and on the duration of the exposure. This is of great importance under safety aspects when classifying the lasers and fixing radiation limits which is also subject of this experiment. By means of two different laser sources all parameters are measured to classify each laser and to determine the limits for which the laser can be considered as safe. This also includes the characterization of laser safety goggles.

2 Fundamentals

This section presents a concise overview of key topics related to laser safety, with a particular focus on tables essential for calculations. This survey and aid is insufficient for comprehending the complete experimental content. It is essential to understand the fundamentals of VBG1, EN 60825-1, or the corresponding literature. The dangers of lasers are well understood due to the characteristic properties of laser radiation. This source of optical radiation is clearly superior to others because it has a high energy and power density. The radiation density is significant even at large distances from the laser because of the generally small beam divergence (this is a potential danger of lasers used in metrology). It is clear that reflected and scattered radiation, in addition to direct radiation, can cause damage from a considerable distance from the radiation source. Table 1 compares radiation densities for different sources. The small radiation density of conventional radiation sources is partially explained by their emission characteristics. The emission is performed into a large solid angle with priority, frequently in approximation into the total space. There are three main sources of danger when using lasers: direct beam, reflection and scattering (in material processing), and non-shielded beams (especially with UV and IR radiation). Another danger is radiation sources that are not stationary, such as scanners and movable mirrors.

Radiation source	Intensity W/cm^2
Solar constant	0.14
Sun with magnifying lens	10^2 - 10^3
Gas flame	10^3
Arc lamp	10^4
Electron beam	10^7 - 10^8
Continuous Laser	10^7
Pulse Laser	10^8
Giant pulse Laser	10^{10} - 10^{14}

Table 1: Comparison of typical radiation intensities for various light sources

Laser radiation can be generated within a broad spectral range. It extends from a few nanometers up to some hundred micrometers and is, in many cases, outside of the visible spectrum. Some examples are shown in Tab. 2. The damage of the biological tissue (skin, eye) depends strongly on the wavelength and on the duration of the radiation. This is of great importance under safety aspects when classifying the lasers and fixing radiation limits. In this regard the maximum permissible radiation values are quite different for the lasers listed in Table 2. the spectral range between 180 nm and 106 nm has been subdivided into 11 sub-ranges with partially exceptionally fine graduation due to actual standards.

Laser	Wavelength nm	cw power/ pulsed peak power
Hydrogen (H_2)	116, 123, 160	-/ 1 MW
Nitrogen (N_2)	337	-/ 5 MW
Excimer	193, 248, 308, 351	-/ 1000 MW
Argon (Ar^+)	488, 514	10W /-
HeNe	543, 594, 632.8	<1W /-
Nd:YAG	473, 532, 1064	2 kW / 1TW
GaAlAs, InGaAsP	650 - 1500	some Watt /-
CO_2	10600	20kW / 100TW
1 kW =1000 Watts, 1 TW = 10^9 kW		

Table 2: Survey of the attainable powers and emission wavelengths of some lasers. Excimer, Nd:YAG and CO2 - lasers are particularly used in material processing

2.1 Laser safety classification according to IEC 825

The classification of lasers into classes clearly indicates an increase in danger with increasing class number. A laser system's potential danger is immediately apparent even to non-experts.

Class 1:

A laser of class 1 is considered as safe over an exposition time not exceeding 8 hours (30000 s). Systems with built-in lasers of higher class number can also be considered in this category (example: CD-player containing a class 3A Diode Laser) if they have been secured with a protective housing with safety interlocks in such a way that under no circumstances Laser light can leave the system.

Class 2:

Lasers of lower power in the visible spectral range (400 –700 nm). The maximum laser power is permitted in maximum up to 1 mW. These lasers are not really safe. Nevertheless, the eye protection is guaranteed by the eye lid reflex (t = 0.25 s). That means if the eye will hit by such a laser beam the natural reflex of shutting the eye is enough to prevent any damage of it.

Class 3A:

Generally, these lasers are safe when looking to it with the naked eye and without optical device like glasses or binoculars. The rule of thumb is:

the maximum power P_L can be 5 mW if the power density E does not exceed a value of 25 W/m^2.

In this case a maximum power of 1 mW can enter the eye without serious danger presuming a pupil diameter of 7 mm. In the non-visible spectral range (UV, IR) the danger for the eye is comparable with the one for lasers of class 1. A direct view into the beam with optical devices is always dangerous and should be avoided.

Class 3B:

Continuous working (cw) Lasers with a maximum power of 500 mW. The radiation is always dangerous for the eye as well as for the skin.

Class 4:

Lasers of class 4 are always dangerous for eyes and skin even due to diffuse reflection. There is danger of fire and explosion.

Although it seems to be simple to classify a certain Laser into one of the 5 safety classes so far, but the knowledge of the output power alone is not sufficient.

Responsible for a damage of the human eye or skin is at least the intensity of the laser beam. Since the intensity is defined as power per square centimeter (W/cm^2) one has to know the actual laser power and the dimension of the laser beam for the location or distance L from the laser for which the safety considerations have to be performed.

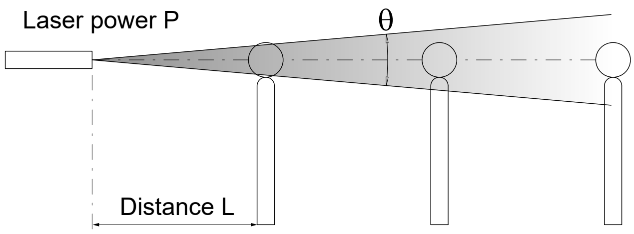

Fig. 1: The larger the divergence θ of the Laser will be the lower the intensity and potential danger will be at more distanced points for an observer

In the next chapter the limits for this intensity or in other words the maximum permissible exposure also termed as MPE value will be discussed in detail.

2.2 The accessible emission limit (AEL)

Limiting values of the AEL are defined for the individual laser classes. Here the wavelength as well as the duration of emission or radiation are the decisive parameters.

Whereas the limiting values for the maximum permissible radiation (MPR) are defined by the wavelength or by a mixture of wavelengths, by the duration of emission (of special importance for pulsed systems) and by the irradiated part of the body (eyes, skin).

For the irradiation of the eye this value is mainly given by the size of the image of the light beam produced on the retina and therefor the subsequent considerations are based on the limits for permitted exposure of the retina. In this context we will briefly discuss the interaction and possible damage of light with biological tissues

The damage of biological tissue through optical radiation is caused by various wavelength dependent mechanisms. Light which is absorbed in tissue is generally converted into heat and causes so-called thermal damages. Furthermore, thermo acoustical and photochemical reactions can occur. Keywords in this context are denaturation of proteins and enzymes, coagulation, explosive evaporation of tissue (cavitation) and photo ablation. Examples of the damaging effect of laser radiation on skin and eyes are represented in Table 3 as a function of the wavelength.

The limiting values, fixed due to standards, differ regarding the effect of laser radiation on:

1) The cornea of the eyes (direct view into the beam)
2) The cornea of the eyes at a view of extended sources or after diffuse reflection
3) The skin

Wavelength	Spectral class	Eyes	Skin
100 - 280 nm	UV-C Far UV	Photo keratitis	Red coloring, burning danger of cancer
280 - 315 nm	UV-B Medium UV	Photo keratitis	Progressive skin aging danger of cancer
315 - 400 nm	UV-A Near UV	Photochemical cataract	Browning, burning photosensitive reactions
400 - 780 nm	Visible	Photochemical and thermal damage of the retina	Browning, burning photosensitive reactions
780 - 1400 nm	IR-A Near IR	Burning of the retina cataract	Burning, photosensitive reactions
1400 - 3000 nm	IR-B Middle IR	Burning of the cornea, cloudiness of lens, streaks in the eye chamber liquid	Burning, photosensitive reactions
3000 - 10000 nm	IR-C Far IR	Burning of the cornea	Burning, photosensitive reactions

Table 3: Examples of the damaging effect of optical radiation on biological tissue. The resulting biological effects are partially used for therapeutically treatment in laser medicine

3.2.1 MPR Values for the Eyes

Here the limiting values within the visible and near IR-range (400 < λ/nm < 1400) are particularly low due to the spectral properties of the human eye. In this wavelength range radiation enters the eye and is focused onto the retina. For a presumed pupil diameter of 7 mm the image on the retina can reach a size of about 10 µm. This corresponds to an increase of the power density by a factor of 500 000.The limiting values, currently fixed for irradiation of the eyes at direct view into the beam (irradiation of the cornea) are shown in Table 5 due to standard EN 60825-1. When calculating the MPR-values the correction factors C_i, T_i must be applied. For exposures under 10^{-9} s there are no or only limited information regarding the effect of ultra-short laser pulses for the time being. For this time range the MPR-values have been derived from the values of an exposure or pulse duration of 10^{-9} s.

Generally, all the MPR-values are below the recognized and scientifically proved risk levels. Nevertheless, they are not to be treated as precise limiting values in between “safe” and “dangerous”.

3.2.2 MPR Values for the Skin

The structure of the limiting values within the spectral range 400 < λ/nm < 1400 is relatively simple for the irradiation of the skin, since - compared with the eye - there is no focusing effect. The relevant part of the actual DIN EN 60825-1 is shown in Tab. 6.

MPR-values irradiation of human skin (DIN EN 60825-1)			
Wavelength	Duration of Exposition t_E in sec		
λ/nm	10^{-7}-10	10-10^3	10^3-$3\cdot10^4$
400-700	$1.1\cdot10^4\ t_E^{0.25}$ J/m^{-2}	2000 W/m^{-2}	2000 Wm^{-2}
700-1400	$1.1\cdot10^4\ t_E^{0.25}$ J/m^{-2}	2000 C_4 W/m^{-2}	2000 C_4 Wm^{-2}
C_4=1 for λ<700nm C_4=$10^{0.002(\lambda-700)}$ for 700< λ/nm <1050 C_4=5 for λ>1050nm			

Table 4: MPR values for irradiated human skin

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MPR-values for the irradiation of the cornea of the eye (direct view into the beam)

Wavelength in nm		Time Duration t of Emission or Exposition in sec.								
		$<10^{-9}$	$10^{-9} – 10^{-7}$	$10^{-7}–1.8{\cdot}10^{-5}$	$1.8{\cdot}10^{-5} –5.0{\cdot}10^{-5}$	$5.0{\cdot}10^{-5}$-10^{-3}	10^{-3} - 10	10-10^3	10^3-10^4	10^4 - $3{\cdot}10^4$
UV	180-302.5	$3{\cdot}10^{10}$ W/cm²	30 J/m²							
	302.5-315		C_1 J/m² (t<T1)			C_2 J/m² (t<T1)		C^2 J/m²		
	315-400		C_1 J/m²					10^4 J/m²	10 W/m²	
VIS	400-550	$5{\cdot}10^{10}{\cdot}C_6$ W/cm²	$5{\cdot}10^{-3}{\cdot}C_4{\cdot}C_6$ J/m²		$18{\cdot}t^{0.75}{\cdot}C_6$ J/m²			$10^2{\cdot}C_6$ J/m²		$10^{-2}{\cdot}C_6$ W/m²
	500-700							$10^2{\cdot}C^3{\cdot}C^6$ J/m² ($t_1>T_2$) $18{\cdot}t^{0.75}{\cdot}C^6$ J/m² ($t_1>T_2$)		$10^{-2}{\cdot}C_3{\cdot}C_6$ W/m²
IR	700-105	$5{\cdot}10^6{\cdot}C_6{\cdot}C_4$ W/cm²	$5{\cdot}10^{-3}{\cdot}C_6{\cdot}C_4$ J/cm²		$18{\cdot}t^{0.75}C_4{\cdot}C_6$ J/m²				$3.2{\cdot}C_4{\cdot}C_6$ W/m²	
	1050-1400	$5{\cdot}10^7{\cdot}C_6{\cdot}C_7$ W/cm²	$5{\cdot}10^{-2}{\cdot}C_6{\cdot}C_7$ J/cm²			$90{\cdot}t^{0.75}{\cdot}C_6{\cdot}C_7$ J/m²			$16{\cdot}C_6{\cdot}C_7$ W/m²	
	1400-1500	10^{12} W/cm²	10^3 J/m²			$5620{\cdot}t^{0.25}$ J/m²		10^3 W/m²		
	1500-1800	10^{13} W/cm²	10^4 J/m²							
	1800-2600	10^{12} W/cm²	10^3 J/m²				$5600{\cdot}t^{0.25}$ J/m²			
	2600 – 10^6	10^{11} W/cm²	100 J/m²	$5620{\cdot}t^{0.25}$ J/m²						

Table 5: Representation of the maximum permissible radiation values, MPR, as a function of the wavelength λ and the duration of exposure t. For calculation the correction factors C_i, T_i as well as suitable aperture diameters must be taken under consideration. (DIN EN 60825-1, 1994)

$C_1=5.6{\cdot}10^3{\cdot}t^{0.25}$	$C_2=10^{0.2\cdot(\lambda-295)}$
$C_3=10^{0.015\cdot(\lambda-550)}$	$C_4=10^{0.002\cdot(\lambda-700)}$ for 700 nm < λ < 1050 nm C_4 = 5 for λ > 1050 nm
$C_5 = N^{-0.25}$	C_6=1 for point light sources
C_7=1 for 1050 nm < λ < 1150 nm $C_7=10^{0.018\cdot(\lambda-1150)}$ for 1150 nm < λ < 1200 nm C_7=8 for λ > 1200 nm	
$T_1 = 10^{0.8\cdot(\lambda-295)} \cdot 10^{-15}$s	$T_2 = 10 \cdot 10^{0.02\cdot(\lambda-550)}$s

Table 6: Definition of Constants used in Table 5

A graphical representation of the maximum permissible energy density as a function of the wavelength and exposure is shown in Fig. 2. Actually, it is an illustration of Table 5. Particular attention must be paid to the logarithmic scaling of the z-axis (MPR values). It is evident that the MPR-values are very low in the visible spectral range between 400 and 700 nm.

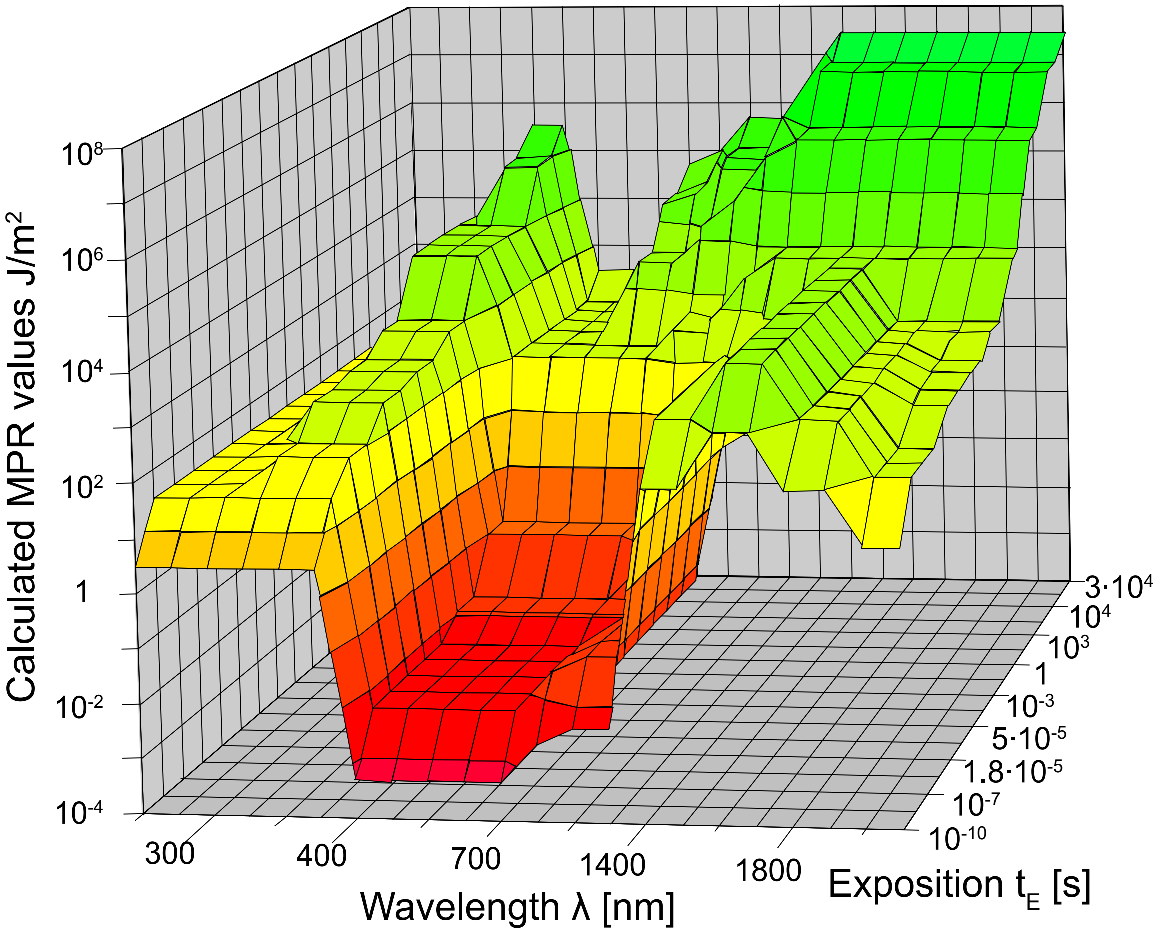


Fig. 2: Logarithmic representation of the MPR values versus the wavelength λ and the exposure time t. Within the visible spectral range ($400 < \lambda/\mathrm{nm} < 700$) the MPR values are particularly low.

3.1 Laser safety goggles

The standards request suitable laser safety goggles for use of laser systems when no other precautions can be taken to avoid the occurrence of dangerous radiation. Actual standards for laser protective glasses are defined for example in EN207 and for laser safety goggles in EN208. These glasses are comparable to a filter with a transmission *τ(λ)*. A measure for the attenuation of a filter is its optical density D.

$$D = -\log \tau(\lambda)$$

Example: an optical density of 6 represents an attenuation factor of 10^{-6}.

Protective class	Spectral transmissions τ(λ)	Maximum permitted Laser power P/Watt	Maximum permitted peak energy Q/Joule
R1	$10^{-2} < \tau(\lambda) < 10^{-1}$	0.01	$2\cdot 10^{-6}$
R2	$10^{-3} < \tau(\lambda) < 10^{-2}$	0.1	$2\cdot 10^{-5}$
R3	$10^{-4} < \tau(\lambda) < 10^{-3}$	1	$2\cdot 10^{-4}$
R4	$10^{-5} < \tau(\lambda) < 10^{-4}$	10	$2\cdot 10^{-3}$
R5	$10^{-6} < \tau(\lambda) < 10^{-5}$	100	$2\cdot 10^{-2}$

Table 7: Representation of the protective classes of the spectral transmission τ (λ) and the maximum permissible casual radiation (no intentional, direct view into the beam) for laser adjustment glasses (complies with DIN EN 208, 12/93)

Theory

Protection classes L	Maximum spectral Transmission $\tau(\lambda)$	Permissible power or energy density in the range of $315 < \lambda/nm < 1400$ for cw-Laser (CW) given in W/m^2, pulse or giant pulse (I, R) given in J/m^2 and mode coupled pulsed lasers (M) given in W/m^2		
		CW	I, R	M
L 1	10^{-1}	10^2	$5 \cdot 10^{-2}$	$5 \cdot 10^7$
L 2	10^{-2}	10^3	$5 \cdot 10^{-1}$	$5 \cdot 10^8$
L 3	10^{-3}	10^4	$5 \cdot 10^0$	$5 \cdot 10^9$
L 4	10^{-4}	10^5	$5 \cdot 10^1$	$5 \cdot 10^{10}$
-	-	-	-	-
L 10	10^{-10}	10^{11}	$5 \cdot 10^7$	$5 \cdot 10^{16}$

Table 8: Representation of the protective classes, the spectral transmission and the permissible power and energy density for laser safety filters used for either safety goggles or protective shields

Laser safety goggles for visible Laser adjustment purposes are characterized by a small attenuation within the visible spectral range and transmit in this range a residual radiation for performing the adjustments. The attenuation is much stronger outside the visible range. The total range is subdivided into five protective classes (Table 8).

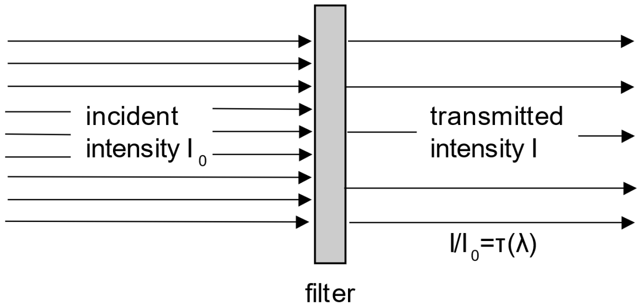


Fig. 3: Illustration of the attenuation of laser radiation by a filter with spectral transmission $\tau(\lambda)$ or optical density D

Laser safety goggles for pure protection and not for Laser alignment purposes are available and classified for a wavelength range between 0.180 and 1000 µm. The protection is maintained even for a direct view into the laser beam. An extract of the protective zones for the spectral range from 315 nm to 1400 nm is shown in Table 7. The basis was a duration of 10 s or 100 pulses at a small pulse repetition rate. The degree of transmission of the protective glasses is not allowed to change under the influence of the laser radiation.

A HeNe-laser beam is, for instance, attenuated by a factor of 10^1 when using a L1 protective class. Depending on the output power of the Laser and the maximum permissible radiation decides which type of protective class should be used.

Theory

4 Basic considerations

To take the right measures for Laser safety reasons one must know the intensity of the considered light source for a given distance. When this intensity is below the MPR value there will be no risk for damaging the eye. The intensity is defined as the flux of radiation passing a cross section of 1 square meter. The flux of radiation is measured in Watts and can be either measured or one trusts the manufacturer of the light source or Laser. Another definition of the intensity is quite often used as radiation namely the flux per solid angle dΩ.

4.1 NOHD, Nominal Ocular Hazard Distance

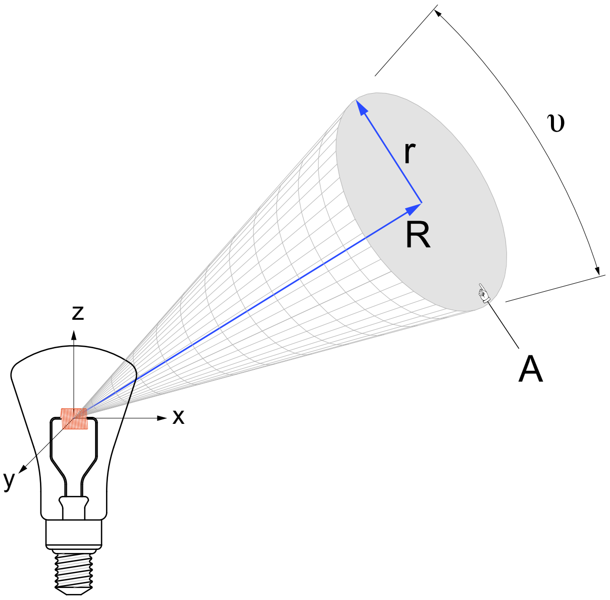


Fig. 4: Definition of the solid angle dΩ

The frequently used expression, “solid angle dΩ” will be clarified once again with the help of Fig. 4. The solid angle dΩ is defined as the ratio of the spherical surface A to the total surface of the sphere of radius R:

$$d\Omega = \frac{A}{4\pi \cdot R^2}$$

For A = 1 m² and R = 1 m (unit sphere) we get the unit of the solid angle, the steradian sr

$$1\text{sr} \equiv \frac{1}{4\pi}$$

The solid angle 1 sr cuts a cone out of the unit sphere with an angle υ (see Fig. 4) If the surface of the corresponding spherical section is approximated by the circular surface π r² we get with

$$A = \pi\, r^2$$

for $A = 1\ m^2$

$$r = \frac{1}{\sqrt{p}}$$

and for υ :

$$\sin\left(\frac{\upsilon}{2}\right) = \frac{r}{R} = \frac{1}{\sqrt{\pi}}$$

or $\upsilon \cong 34°$

The light that passes by the solid angle unit is called radiant intensity I_e and is measured in W/sr. To measure the radiant intensity in Wsr¹, it is necessary to know the solid angle used during the measurement. A diaphragm with a radius r is used for this purpose and a distance R to the radiator is selected. The solid angle dΩ for this arrangement is therefore

$$d\Omega = \frac{\pi \cdot r^2}{4 \cdot \pi \cdot R^2} = \frac{1}{4} \cdot \frac{r^2}{R^2}$$

If, for example, the radius of the diaphragm is 15 mm and the distance to the light source is 80 cm, the solid angle will be

$$d\Omega = \frac{1}{4} \cdot \frac{0{,}015^2}{0{,}8^2} = 8{,}79 \cdot 10^{-5}\,\text{sr}$$

If the total emitted radiation into the full solid angle of 4π is 250 mW, for example, the flux P_e through the diaphragm will be:

$$P_e = P_\Omega \cdot \frac{d\Omega}{\Omega} = P_\Omega \frac{1}{4\pi} \cdot \frac{A_d}{A_R}$$

and the intensity:

$I_e = \frac{P_e}{A_d} = P_\Omega \cdot \frac{1}{4\pi} \cdot \frac{1}{A_\Omega} = P_\Omega \cdot \left(\frac{1}{\pi \cdot R}\right)^2$	**(Eq 1)**

$$I_e = P_\Omega \cdot \left(\frac{1}{\pi \cdot R}\right)^2 = 0.25 \cdot \left(\frac{1}{\pi \cdot 0.8}\right)^2 = 0.04\frac{W}{m^2}$$

From (Eq 1)we can deduce, that for a fixed aperture the intensity will decrease inverse quadratically with increasing distance R from the light source.

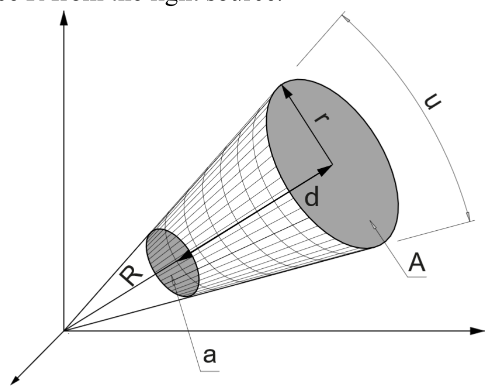


Fig. 5: Fig. 5: Surface emitter

From the surface the light source emits the power P_0. In point of view of laser safety, we must know the intensity at a distance d where for instance the eye of the observer is located. The intensity at the surface is simply

$$I_s = \frac{P_0}{a}$$

and the intensity at the distance d will be:

$$I_d = \frac{P_0}{A}$$

Commonly the cross-section a as well as the beam radius r_a is known and we have to derive an expression for A. Since

$$r_A = r_a + 1 \cdot \tan\left(\frac{\vartheta}{2}\right)$$

we find for the intensity I_d:

$$I_d = \frac{P_0}{\pi \cdot \left(r_a + 1 \cdot \tan\left(\frac{\upsilon}{2}\right)\right)^2}$$

If we consider the case of Laser beam, we know that the divergence or the angle υ is fairly smaller than 15 °. In this case we can use the approximation:

$$\tan(\vartheta) \cong \vartheta$$

To be in accordance with the IEC 825 nomenclature we now will assign the beam diameter of the laser beam to d_0, the distance from the Laser exit as *z*, the intensity at location *z* as *E* and finally the divergence angle as θ.

$$E = \frac{4 \cdot P_0}{\pi \cdot (d_0 + z \cdot \theta)^2} \qquad \textbf{(Eq 2)}$$

A Laser can be considered as save when for each distance z

$$MPR \le E \qquad \textbf{(Eq 3)}$$

For a particular Laser the MPR is taken from Table 5. With the specification given by the supplier the value for E is calculated using the power, the beam diameter at the beam exit, the divergence and the location for which the (Eq 3) must be fulfilled. It may happen, that (Eq 3) is only true for a certain distance z. The minimum of the distance where the Laser can be considered as save is termed as nominal ocular hazard distance or as NOHD. This value can be derived from (Eq 2) and (Eq 3) as:

$$z_{NOHD} = \frac{1}{\theta} \cdot \left(\sqrt{\frac{4P}{\pi \cdot MPR}} - d_0\right) \qquad \textbf{(Eq 4)}$$

If a negative value for z_{NOHD} is obtained, the laser is safe and means total safety for each distance.

4.1.1 NOHD for diffuse radiator

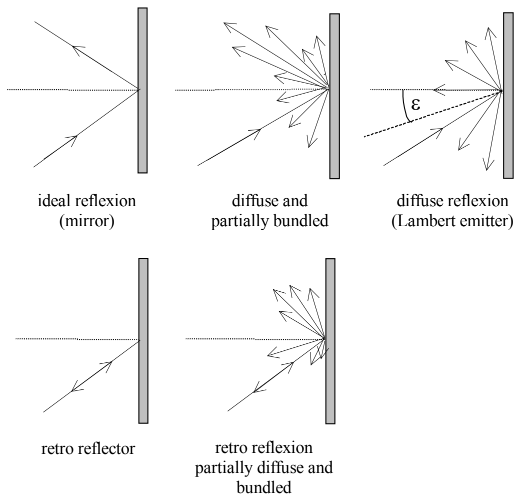


Fig. 6: Different types of reflection and corresponding light intensity distributions

By scattering and diffuse reflection, the light energy is distributed in a more or less extended space depending on the type of scattering surface. (see Fig. 6) The scattering surface can be considered as a “secondary light source” with modified radiation properties. For the diffuse scattering of a laser beam a hemispherical surface A is anticipated as irradiated area for the approximate calculation of the power density E. It is presumed that the radiating surface emits isotropic into the halve solid angle 2π and onto a considered surface of area $A = 2\pi r^2$. The distance to the scattering surface shall be large compared to its diameter. In this case we consider the scattering surface as point source as discussed earlier ((Eq 1)). But know we must modify the equation since the emission fills only the half solid angle, therefor:

$$E = 2 \cdot P \cdot \left(\frac{1}{\pi \cdot z}\right)^2 \qquad \textbf{(Eq 5)}$$

Setting E to MPR to derive the NOHD for diffuse scattered Laser light we obtain the expression for z_{NOHD} :

$$z_{NOHD} = \frac{1}{\pi} \cdot \sqrt{\frac{2 \cdot P}{MPR}}$$

4.2 MPR values for pulsed radiation

4.2.1 Criteria:

- the irradiation by each single pulse within a pulse sequence is not permitted to pass the permissible value of a single laser pulse MPR_{single}
- the MPR-value for the average irradiation of a pulse sequence of duration T ($MPR_{average}$) is not allowed to pass the MPR-value of the irradiation by a single laser pulse of equal duration T. (equiv. pulse, no passing of $MPR_{equiv.}$)
- the irradiation by each single laser pulse within the pulse sequence is not allowed to pass the MPR-value of a single pulse multiplied by the correction factor C_5 (see Table 5)

Theory

4.2.2 Conclusion:

From all determined MPR-values

$$(MPR_{single}, MPR_{average}, MPR_{corr.})$$

the most limiting value is decisive. That means this MPR-value must be applied to each individual laser pulse. Summarizing the steps for the determination of the MPR-value for a pulsed laser system.

- Fixing the exposure T of the pulse sequence (for example 0.25 s in the visible spectral range)
- Determination of the duration τ_p of a single laser pulse
- Determination of the number of pulses N_T during the exposure T
- Determination of the MPR-value for a single laser pulse from Tab. 4 ($HMPR,_{single}$)
- Determination of the MPR-value for an average radiation; here the MPR-value for an equivalent pulse of exposure T is determined from Table 5.
- The average MPR-value is then calculated by

  $$H_{MPR, average} = H_{MPR, equiv.} / N_T$$
- Determination of the MPR-value for a single pulse in connection with a correction factor
- For the number of pulses during the exposure

  HMPR, corr = HMPR, single C5
- Selection of the most limiting MPR-value (smallest value from $H_{MPR, single}$, $H_{MPR, average}$, $H_{MPR, corr.}$)

Supplement: For irregular pulse sequences (example: modulated laser diodes) the highest instantaneous frequency (reciprocal value of the shortest pulse distance) must be considered.

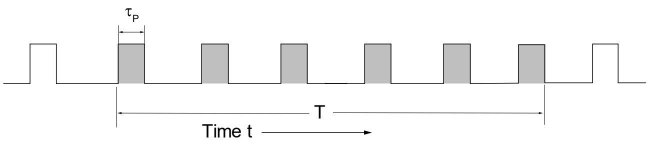


Fig. 7: Fig. 7: Regular pulse sequence.

The time T has been chosen for exposure. Six individual laser pulses are observed within the interval T. The temporal duration of a single laser pulse is τ_P.

4.3 ABCD Law

In the following section, the fundamental principles employed in the description, calculation and measurement of beam divergence will be introduced, along with the ABCD law in this context.

The ABCD matrix formalism constitutes a sophisticated technique for tracing the trajectory of a beam (ray tracing) within a complex optical system.

Firstly, it is necessary to assume that the subsequent calculations are accurate for the limits of geometric optics. This is to say that if the beam angle is less than 15° to the optical axis, then $\sin\alpha \cong \tan\alpha \cong \alpha$. It has been demonstrated that this is the case in most systems, particularly in the context of laser rays. The height of a light beam is defined by its distance from the optical axis, and the slope at the point of intersection is also a key factor (**Fig. 8**).

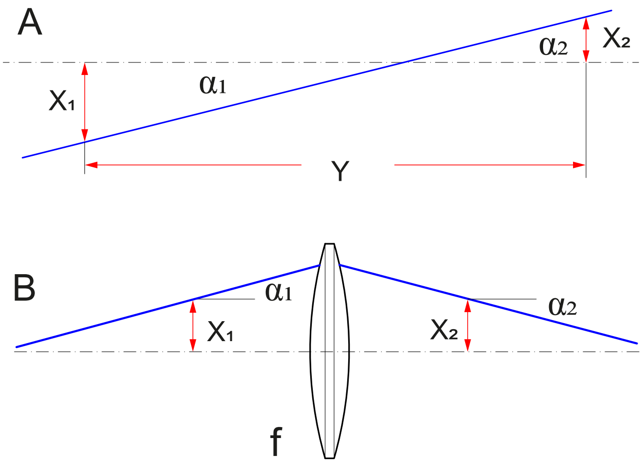


Fig. 8: (A) light beam with the characteristic parameters, (B) trace through a lens.

The matrix to be introduced is called the ray transfer matrix or ABCD matrix. When this matrix is applied to the input quantities x_1 and α_1 the resulting output quantities will be x_2 and α_2:

$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

The example A of Fig. 8 shows the free propagation of a beam, from which we can deduce that $\alpha_1 = \alpha_2$ and $x_2 = x_1 + \alpha Y$. So, the ABCD matrix in this case is:

$$A = \begin{pmatrix} 1 & y \\ 0 & 1 \end{pmatrix}$$

In example B which shows a thin lens the matrix is:

$$B = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

Positive values of f are for a convex and negative values for a thin concave lens. It is easy to understand, that the combination of example A and B is a result of free beam propagation with subsequent focusing with a thin lens

$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = A \cdot B \cdot \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} 1 & y \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

In the following example, we want to calculate the beam path of a thin biconcave lens (Fig. 9) using the ABCD method.

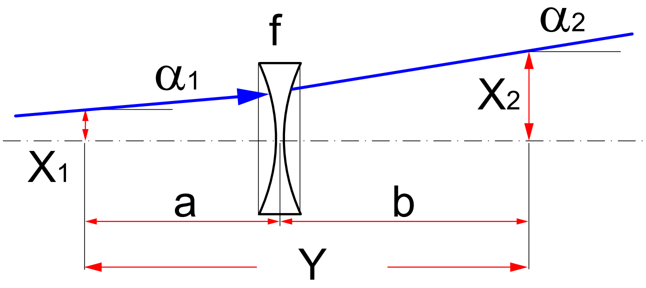


Fig. 9: Example for a thin concave lens

The distance Y can also be defined by the values a and b (see Fig. 9).

In the first step, we calculate

$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} 1 & y \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix} = \begin{pmatrix} 1 & y \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ -\frac{x_1}{f} + \alpha_1 \end{pmatrix}$$

and finally:

$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} 1 & y \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ -\frac{x_1}{f} + \alpha_1 \end{pmatrix} = \begin{pmatrix} x_1 - y\frac{x_1}{f} + y\alpha_1 \\ -\frac{x_1}{f} + \alpha_1 \end{pmatrix}$$

From the last equation, we obtain the expression for x_2:

$$x_2 = x_1\left(1 - \frac{y}{f}\right) + y\alpha_1$$

and for

$$\alpha_2 = -\frac{x_1}{f} + \alpha_1$$

If we measure the divergence α_2 caused by the lens with focal length f for a given distance x_1, the initial divergence α_1 can be calculated.

$$\alpha_1 = \alpha_2 + \frac{x_1}{f}$$

For the classification of a laser, we need to know the intensity I which is defined as

$$I = \frac{P}{A}$$

where P is the power in W and A the cross-section in m^2.

Typically, the laser beam has a low divergence and a small cross-section. One simple method to determine the divergence of a laser beam, is to measure the beam diameter in several meters distance, where the cross-sections becomes that large, that the beam diameter can be measured. However, this is not always possible. With a suitable concave lens (BCL) with known focal length the distance can be reduced to some ten centimeters.

4.4 Measurement Example

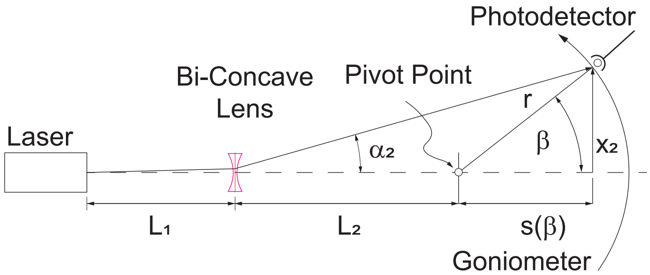


Fig. 10: Experimental situation (see also Fig. 29)

In this setup, the biconcave lens is not located at the pivot point of the goniometer. The angle β of the photodetector, located at a radius of r from the pivot point, is measured. These parameters are used to calculate the actual angle α_2 whereby $y=L_1+L_2+s(\beta)$.

$$x_2 = x_1\left(1-\frac{y}{f}\right)+y\alpha_1$$

$$\alpha_1 = \alpha_2 + \frac{x_1}{f};\ x_1 = f\frac{x_2-y\alpha_1}{f-y}$$

$$\alpha_1 = \alpha_2 + \frac{x_2-y\alpha_1}{f-y} = \alpha_2 + \frac{x_2}{f-y} - \frac{y\alpha_1}{f-y}$$

$$\alpha_1\left(1+\frac{y}{f-y}\right) = \alpha_2 + \frac{x_2}{f-y}$$

$$\alpha_1 = \frac{\alpha_2+\frac{x_2}{f-y}}{1+\frac{y}{f-y}} = \frac{\alpha_2(f-y)+x_2}{f-y+y}$$

$$\alpha_1 = \frac{\alpha_2(f-y)+x_2}{y}$$

From Fig. 10, we see that the value for y is given by:

$$y = L_1+L_2+s(\beta)$$

$$\cos(\beta) = \frac{s}{r};\ s = r\cos(\beta)$$

$$y = L_1+L_2+r\cos(\beta)$$

Using the parameters of the experimental setup, we now want to determine the divergence of the laser used. We determine the angular position (β=60°) of the photodiode at which the intensity is at a minimum. Using this value, we determine the direct angle α to the lens.

$$\cos(\alpha_2) = \frac{x_2}{L_2+r\cos(\beta)}$$

$$\cos(\alpha_2) = \frac{x_2}{L_2+r\cos(\beta)}$$

$$x_2 = r\sin(\beta)$$

$$\cos(\alpha_2) = \frac{r\sin(\beta)}{L_2+r\cos(\beta)}$$

L1 = 0.100 m
L2 = 0.250 m
r = 0.045 m
f = -0.01 m

At the angle position β=60°of the photodetector we noticed the minimum intensity which corresponds to an angle α_2 of 6°. We now use these values to calculate the beam divergence of the laser used.

$$\alpha_1 = \frac{\alpha_2(f-y)+x2}{y}$$

$$= \alpha_2\frac{f}{y} - \alpha_2 + \frac{x_2}{y}$$

$$= \alpha_2\frac{f-x_2}{y} = \alpha_2\frac{f-r\cdot\sin(\beta)}{y}$$

$$= \alpha_2\frac{f-r\cdot\sin(\beta)}{L_1+L_2+r\cdot\cos(\beta)}$$

$$= 6°\cdot\frac{-0.01-0.045\cdot\sin(60°)}{0.350+0.045\cdot\cos(60°)}$$

$$= 6°\cdot\frac{-0.01-0.045\cdot 0.866}{0.350+0.045\cdot 0.5} = \frac{-0.049}{0.373} = -0.13°$$

$$\alpha_1(mrad) = \alpha_1(°)\cdot\frac{2\pi}{360} = 0.0023\,rad$$

$$= 2.3\,mrad$$

With the calculated beam divergence, we can now determine the laser intensity at a specific distance x from the laser source. Let‘s assume that our laser emits a power of 5 mW.

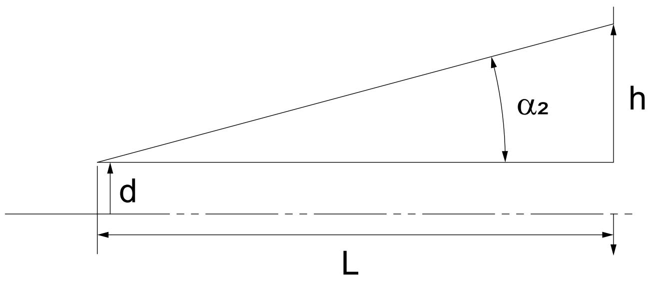


Fig. 11: Beam propagation and cross section

The laser beam has a radius of d at the exit and a divergence angle of α_2=6°. The circular beam cross section covers an area at the distance L of:

$$A = \pi\cdot(d+h)^2.$$

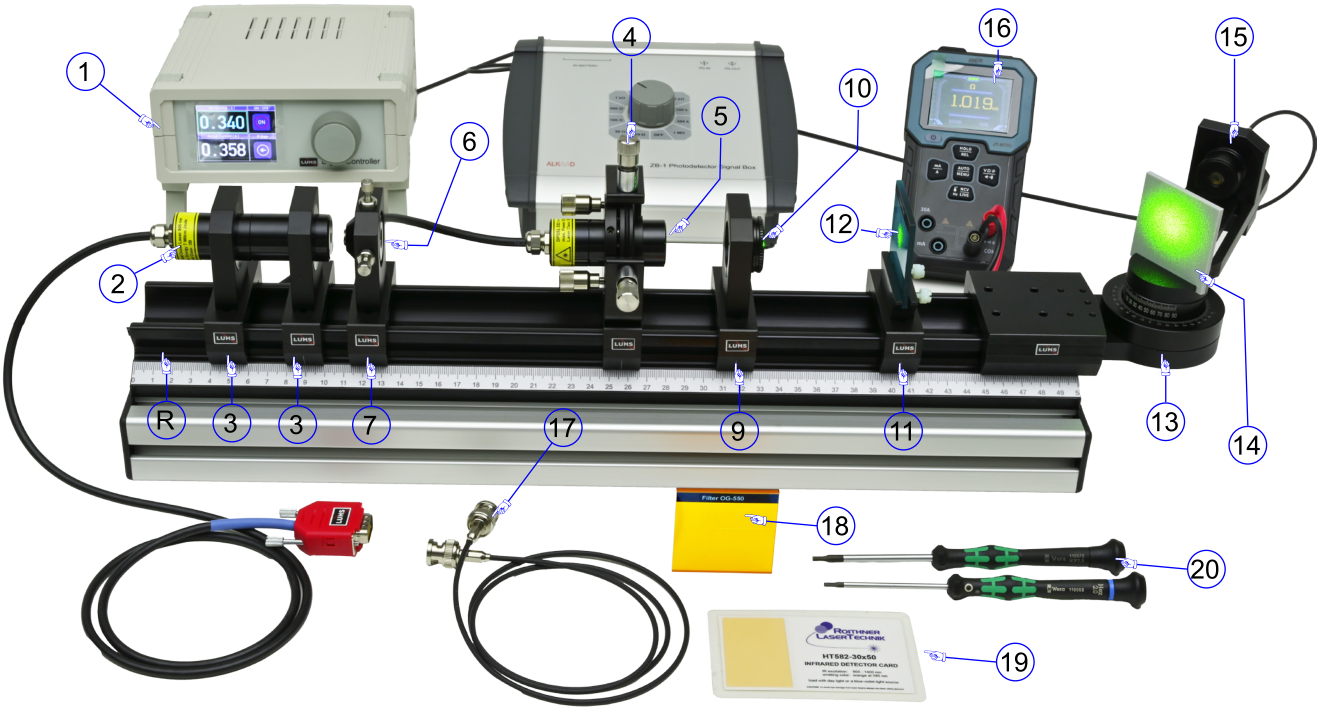
The intensity at a distance for instance of 1 meter is then:

$$A = \pi\cdot(L\cdot\tan(\alpha_2)+d)^2 = 0.0112m^2$$

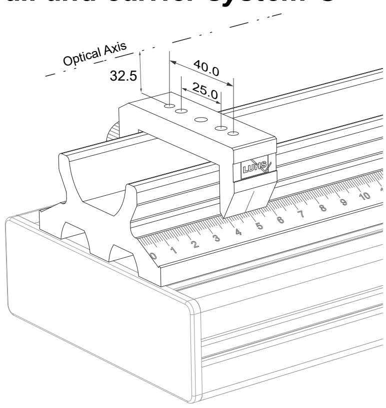
$$I = \frac{0.005W}{0.0112m^2} = 0.446\frac{W}{m^2}$$

Theory

5 Experimental Setup



5.1 The rail and carrier system ®



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 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.

5.2 Diode Laser Controller (1)

Fig. 12: Controller DC-0050 for pulsed and cw laser

Fig. 13: Back side of DC-0050

The laser diode module (2, 5)is connected via the 15 pin HD SubD jacket (LED/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 sim ply by using the same USB bus.

The MK1 provides an internal modulator which allows the periodic on/off switch of the diode laser. A buffered synchronization signal is available via the BNC jacket (MODULATOR).

Further detailed specifications are given in the following section of the operation software.

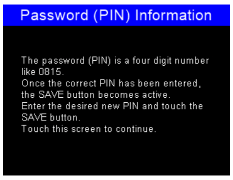
When the external 12 V is applied, the controller starts displaying the screen as shown in the figure below.

Fig. 14: Start screen

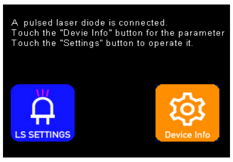
5.2.1 Laser Safety

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 PIN, the next screen is displayed, and the system is ready for operation.

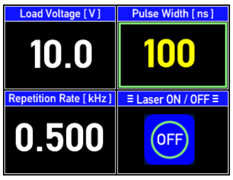
Touch "HOW TO?" brings up the next screen



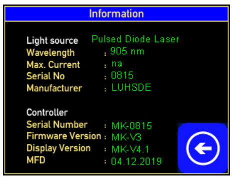
This screen explains how to change the password.



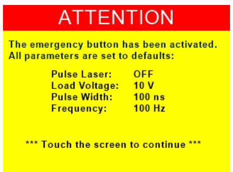
The controller detects what kind of laser source is connected and displays the related settings screen. The figure on the left shows the case for the pulsed laser.



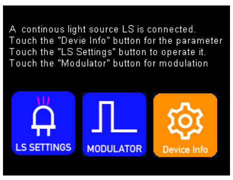
Touching the "LS SETTINGS" button activates the settings. To change a value, touch the display and the selected field is highlighted. Turning the settings knob sets the desired value instantly. The limits are read from the EEPROM of the connected laser diode.



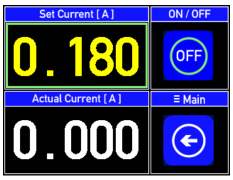
Touching the "Device Info" button shows the information screen displaying details of the connected light source and the controller itself.



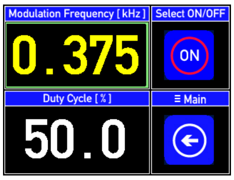
After pressing the adjustment button, the emergency state is activated. All parameters are reset to their default values.



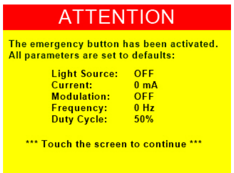
If a continuous light source is connected, the upcoming screen allows to select the "LS SETTINGS", "MODULATOR" and "Device Info".



For immediate "Laser OFF" just tap the OFF/ON button. To set the injection current simply touch the injection current display and turn the settings button.



The diode laser can be switched periodically on and off. Touching the display of the modulation frequency, the entry is activated. Turning the settings knob sets the desired frequency value. The modulation becomes active when the Modulator ON/OFF button is touched.



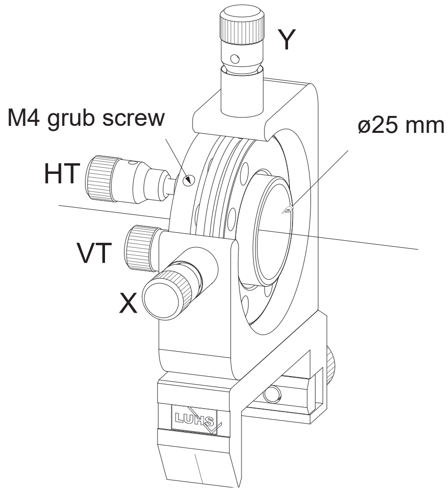
After pressing the setting knobs, the emergency event is activated. All parameters are set to their default values.

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

5.3 LQ-0350 Pulsed diode laser (2)

This diode laser emits pulsed radiation only when it is connected to the controller DC-0050. The controller provides the necessary voltage to load the ignition condenser inside the laser head and the discharge pulse to release the laser pulse. The emission wavelength is 905 nm with a repetition rate of 2 kHz and an adjustable pulse width of 50 to 150 ns and an output energy of 4 µJ. The peak power is 70W.

5.4 MM-0420 Four axes kinematic mount (4)



This frequently needed component is ideal for the fine adjustment of lenses, microscope objectives, diode laser, etc. with respect to the optical axis of the rail set-up. The displacement area is 5x5 mm and 10x10 degrees, respectively. Different mounts can be attached to the adjustment holder. This model provides a holder for 25 mm cylindrical components. The component is inserted into the adjustment holder and is kept in position by a spring-loaded steel ball in the same way as for the lens click mounts. Four precise fine pitch screws of repetitious accuracy allow the translational (X; Y) and azimuthal (HT, VT) adjustment

5.5 LQ-0020 Green (532 nm) DPSSL (5)

A green (532 nm) emitting DPSSL (Diode Pumped Solid State Laser) is integrated into a C25 housing and is operated with the DC-0050 Controller. The output power is < 5 mW. The diode laser is connected via a 15 pin SubD HD connector to the controller MK2. Inside the connector an EEPROM contains the data of the laser diode and when connected to the controller, these data are read and displayed by the controller.

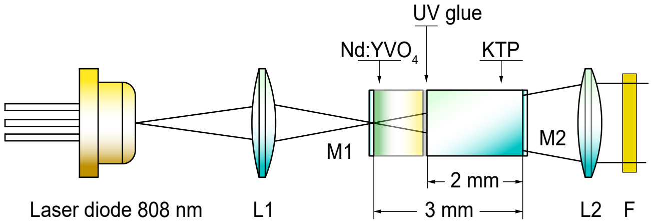
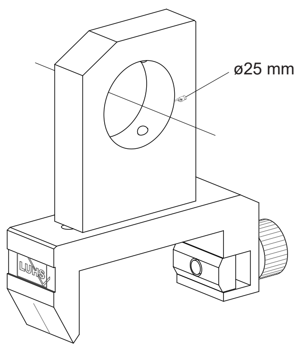


Fig. 15: Principle of a DPSSL module

The DPSSL consists of a pump laser diode whose 808 nm radiation is focused into a neodymium vanadate crystal using a focusing lens. One side of the neodymium vanadate crystal is coated with a mirror layer and forms the resonator mirror M1. The crystal is optically bonded to a frequency doubler crystal (KTP). The KTP is also coated with a mirror layer M2, thus forming the laser resonator. The neodymium vanadate crystal pumped at 808 nm generates intense laser radiation with a wavelength of 1064 nm. The resonator-internal KTP crystal partially converts this radiation into 532 nm, which then leaves the resonator and is collimated with a lens. The filter F is designed to completely block the remaining radiation of 808 nm and 1064 nm. Commercially available laser pointers sometimes lack this filter, and this NIR radiation, which can be quite powerful, is emitted with the 532 nm.

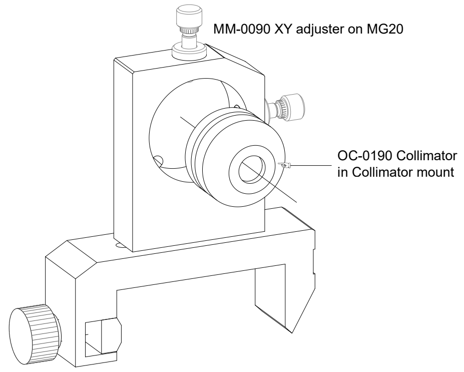
In this experiment, this behavior is investigated using two filters, a BG39 and an OG550.

5.6 MM-0020 Mounting plate C25 on carrier (3, 9)



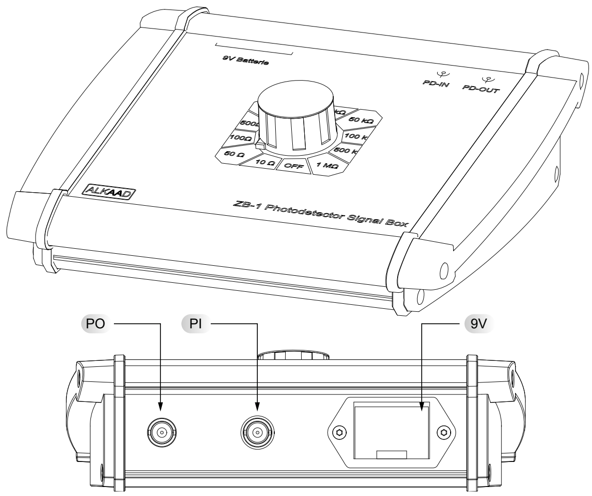
This frequently used component is ideal to accommodate parts with a diameter of 25 mm where it is kept in position by three spring loaded steel balls. Especially C25 mounts having a click groove are firmly pulled into the mounting plate due to the smart chosen geometry. The mounting plate is mounted onto a 20 mm wide carrier.

5.7 MM-0090 XY adjuster on (7) and OC-0170 Collimator in C25 mount (6)



A high precision aspheric glass lens is mounted into a click holder (A) which is inserted into the XY adjuster. With the fine pitch screws the collimator (OC-0170) can be adjusted accordingly. The glass lens has a focal length of 4.6 mm, the numerical aperture is 0.53 and the clear opening is 4,9 mm. In addition, the lens has an anti-reflex coating in a spectral range of 700 - 900 nm with a residual reflection of < 0.5 %.

5.8 DC-0380 Photodetector Junction Box (8)



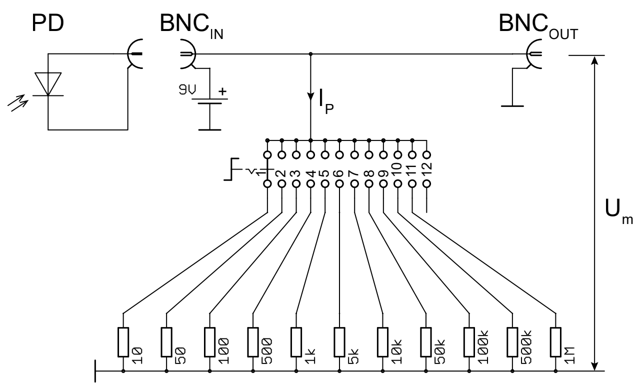


Fig. 16: Internal circuitry of the junction box

The signal box contains a resistor network and a replaceable 9V battery and is prepared to accept all kinds of photo-diodes provided they are connected to the BNC input (PD_{IN}) as shown in the schematic of Fig. 16. At the output PD_{OUT} of the signal box a signal is present which is given by the following equation:

$$I_P = \frac{U_P}{R_L}$$

I_P is the photocurrent created by illuminating the photodiode with light.

U_m is the voltage drop across the selected load resistor R_L.

To convert the measured voltage into a respective optical power we make use of the spectral sensitivity S(λ) [A/W] which depends on the wavelength of the incident light according to Fig. 18. The detected optical power P_{opt} in W can be given as:

$$P_{opt} = \frac{I_P}{S(\lambda)} \qquad \textbf{(Eq 6)}$$

Assuming a wavelength of 700 nm we take the value of S_{rel} from Fig. 12 as 0.8 and subsequently the value of

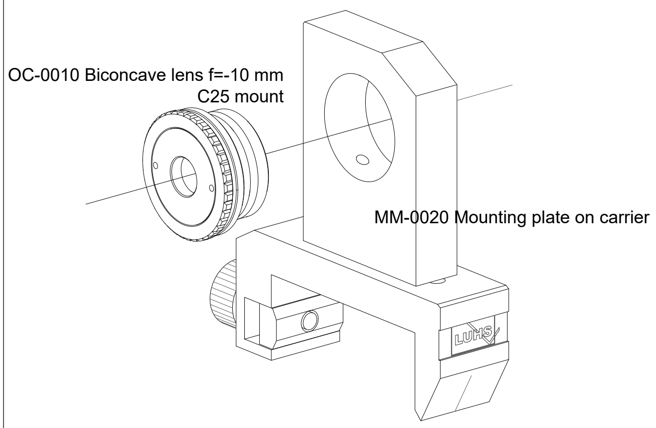
S(λ=700nm) is 0.62 x 0.8 = 0.496

If we are measuring a voltage U_m of 1V with a selected resistor R_L of 1K the optical power will be

$$P_{opt} = \frac{I_P}{S(\lambda)} = \frac{U_m}{R_L \cdot S(\lambda)} = \frac{5}{1000 \cdot 0.496} = 10\,mW$$

It must be noted that the measured power is only correct if the entire light beam hits the detector.

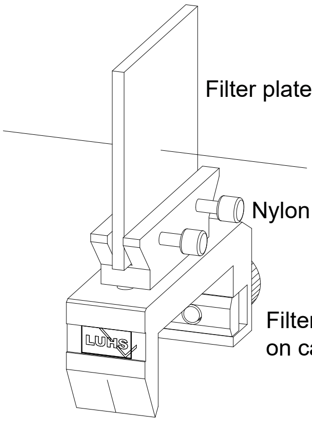
5.9 OC-0010 Biconcave lens f=-10 mm



A biconcave lens with a diameter of 10 mm and a focal length of -10 mm is mounted into a C25 mount with a free opening of 8 mm. The MM-0020 mounting plate on a carrier 20 mm accommodates the lens.

Experimental setup

5.10 MM-0060 Filter plate holder (11)



This filter plate holder is designed to accommodate standard optical filter plates with a thickness of 3 mm, a width of 50 mm and a height of 50 mm. The plate is held in position by two nylon clamping screws.

5.11 Filter BG 39(12)

This colored glass filter has a size of 50x50 mm and a thickness of 3 mm and is used to block the near infrared radiation above 700 nm and transmit the green 532 nm radiation created by second harmonic generation. The transmission curve is shown in Fig. 17.

5.12 Filter OG 550 filter (18)

This coloured glass filter has a size of 50x50 mm and a thickness of 3 mm and is used to block the radiation below 550 nm and transmits the radiation up to 1200 nm. The transmission curve is shown in Fig. 17. This filter is used to verify NIR radiation of green DPSSLs

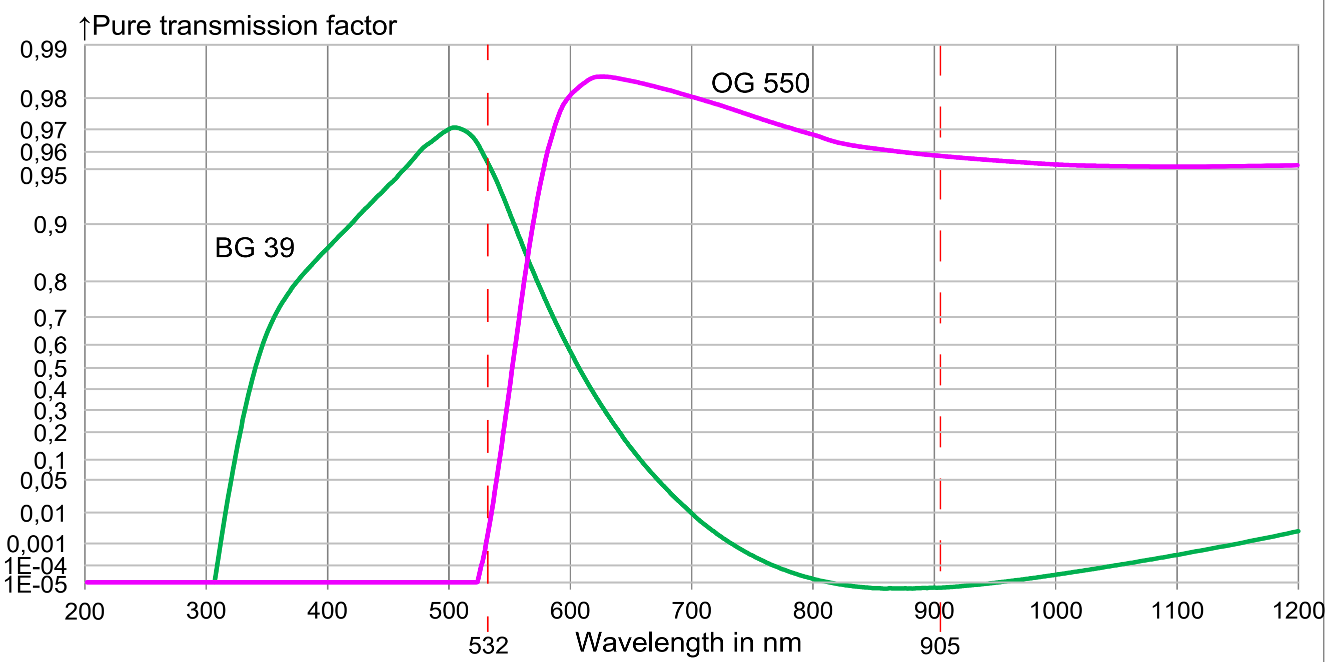
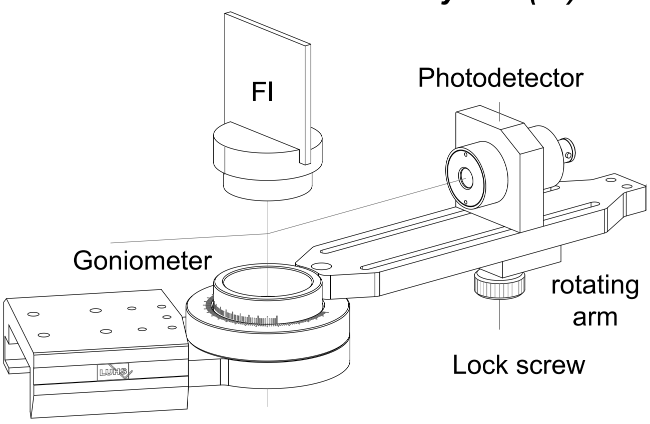


Fig. 17: Transmission curves of the BG 39 and OG 550 filter

Experimental setup

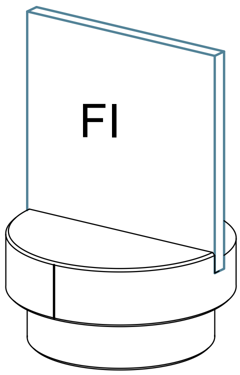
5.13 MM-0300 Carrier with rotary arm (13)



Carrier with 360° rotary arm

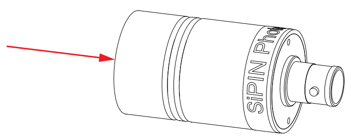
The MM-0300 provides goniometer operation for the optical bench. The carrier is attached to the bench and carries a rotary arm which can be rotated by 360 degrees. The centre of rotation provides a 35 mm mounting hole where probes can be accommodated. The rotating arm is fixed to the goniometer and carries a movable mounting plate to accommodate the photodetector. The mounting plate can be moved along the arm when loosening the lock screw and locked in the desired position.

5.14 MM-0340 Scatter probe (14)



The rotary table fits into the MM-0300 and carries a light-grey plastic plate with 50x50x3 mm. It is used to measure the scattered light of a light source hitting the surface.

5.15 DC-0120 Si-PIN Photodetector (15)



A Si PIN photodiode is integrated into a 25 mm housing with two click grooves (PD). A BNC connector is attached to connect the module to the photodetector signal box ZB1. The photodetector module is placed into the mounting plate (MP) where it is kept in position by three spring loaded steel balls.

Parameter		
Rise and fall time of the photo current at: R_l=50 Ω, Vr=5V, λ=850 nm and Ip=800 µA	τ_r, τ_f	20 ns
Forward voltage I_f = 100 mA, E = 0	Vf	1.3 V
Capacitance at Vr = 0, f = 1 MHz	C_0	72 pF
Wavelength [nm] of max. sensitivity	λ_{Smax}	850
Spectral sensitivity S~10% of Smax	λ	1100
Dimensions of radiant sensitive area [mm²]	L x W	7
Dark current [nA], Vr = 10 V	Ir	≤30
Spectral sensitivity [A/W], λ = 850nm	S(λ)	0.62

Table 9: Basic parameters of Si PIN photodiode BPX61

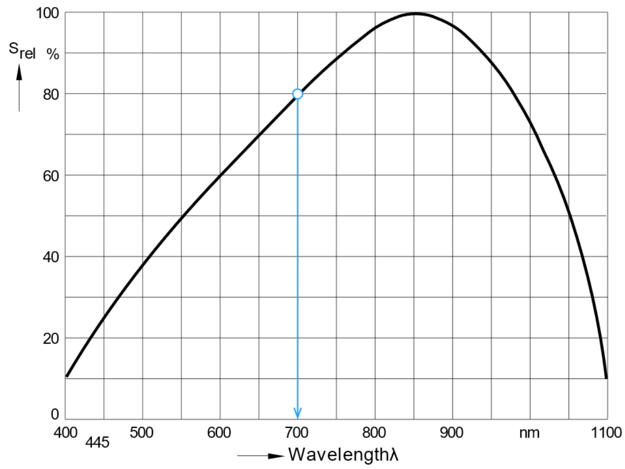


Fig. 18: Sensitivity curve of the BPX61 photodiode

5.16 Infrared detector card (19)

The emitted radiation of the pulsed diode laser has a wavelength of 905 nm which is not visible to the human eye.

Fig. 19: Infrared detector card

The infrared detector card is used to check the beam parallelism and location.

5.17 Allan Screw Driver

The Allen screwdrivers are used to set up M4 screws (¤ 2.5) mm in the assembly or to tighten the M4 grub screws (¤ 2.0) of the four axes kinematic mount.

6 Measurements

6.1 Properties of the pulsed diode laser

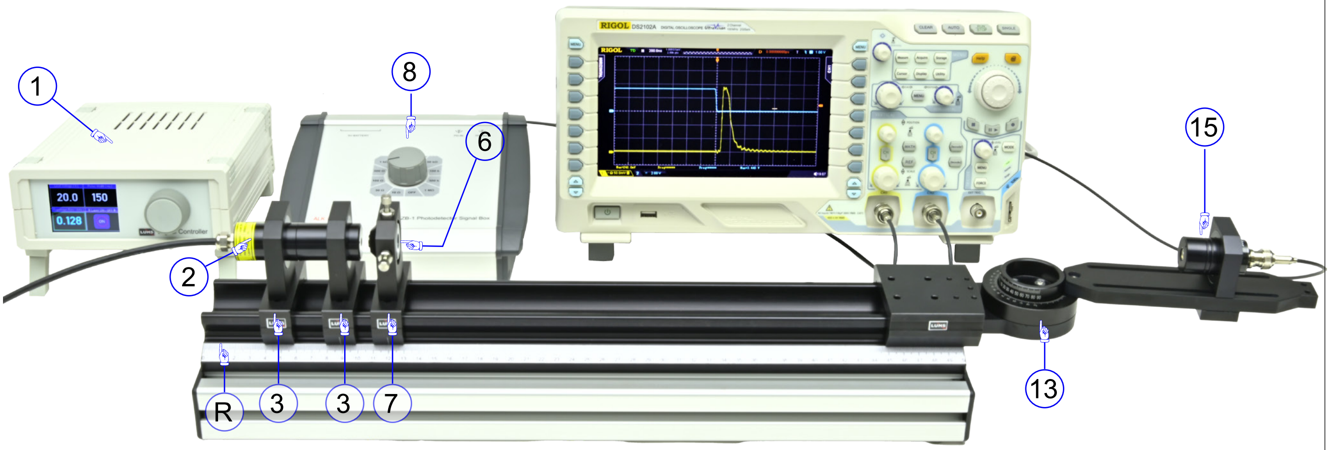


Fig. 20: Setup to characterize the pulsed diode laser

For this part of the experiment, we will investigate the properties of a pulsed laser diode. To accomplish this, we will insert the diode laser module (2) into the two mounting plates and place it on the optical bench (R). The collimator, consisting of collimation optics (6) and an XY adjustment holder (7), is placed on the bench in front of the diode laser module (2). The pulsed laser diode is controlled by the digital controller (1). Set the goniometer to zero degrees to align the photodiode with the optical axis.

Connect the photodetector to the connection box (8) using the supplied BNC cable. The output signal from the connection box is connected to the first channel of the oscilloscope. The reference signal from the controller is connected to the oscilloscope's second channel and serves as a trigger signal.

The controller (1) can be used to adjust the charging voltage for the discharge capacitor, as well as the pulse repetition rate and duration. The following figures show oscilloscope images with their corresponding parameters.

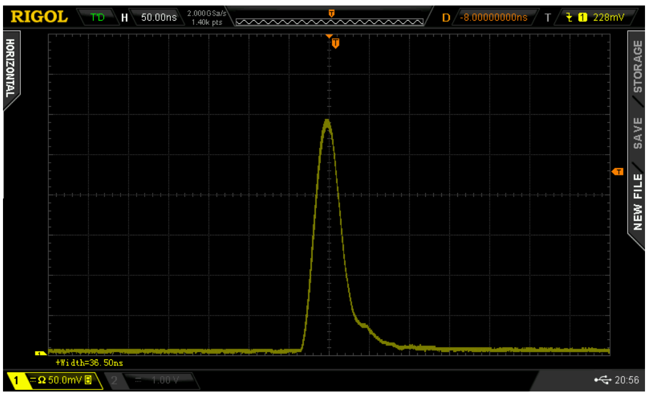


Fig. 21: Light pulse, settings 35 ns 10 V

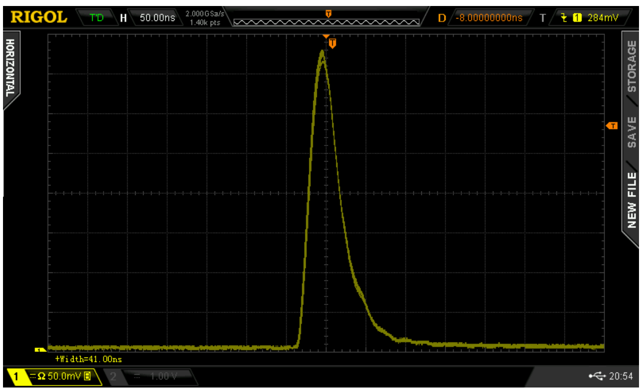


Fig. 22: Ligh pulse, settings 35 ns 20 V

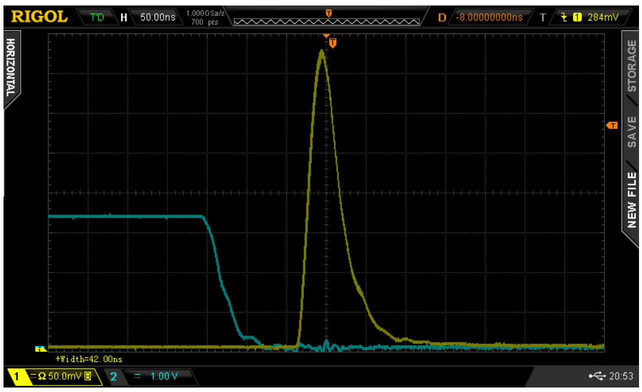


Fig. 23: 35 ns 20V with trigger signal

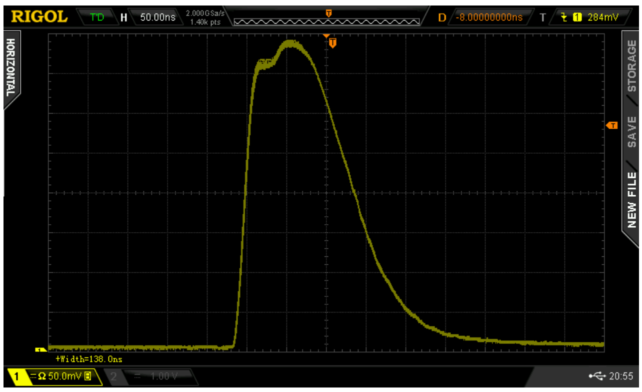


Fig. 24: Light pulse, settings 150 ns, 20V

6.2 Average and peak power

Given the peak power of a pulse, the average power P_{av} can be calculated using the following formula:

$$P_{av} = P_{peak} \cdot t_p \cdot r_{rate}$$
$$= 70\,W \cdot 150 \cdot 10^{-9} \cdot 2000 = 0.021\,W$$

Here, t_p is the pulse duration and r_{rate} is the repetition rate. For example, with a peak power of 70 W, a pulse duration of 150 ns, and a repetition rate of 2,000 pulses per second, the average power (Pav) is 21 mW. The peak power can be determined using the photodetector when the laser beam nearly fills the detector area. To avoid saturation effects, one of the two filters can be used to reduce the power reaching the detector. The measurements can also be used to determine the energy E_p per pulse using the following formula:

$$E_P = P_{peak} \cdot t_p = 70\,W \cdot 150 \cdot 10^{-9} = 10.5\,\mu J$$

When optical energy or power is measured with a calibrated sensor, reliable values for laser classification can be obtained.

6.3 Measuring scattered light intensity

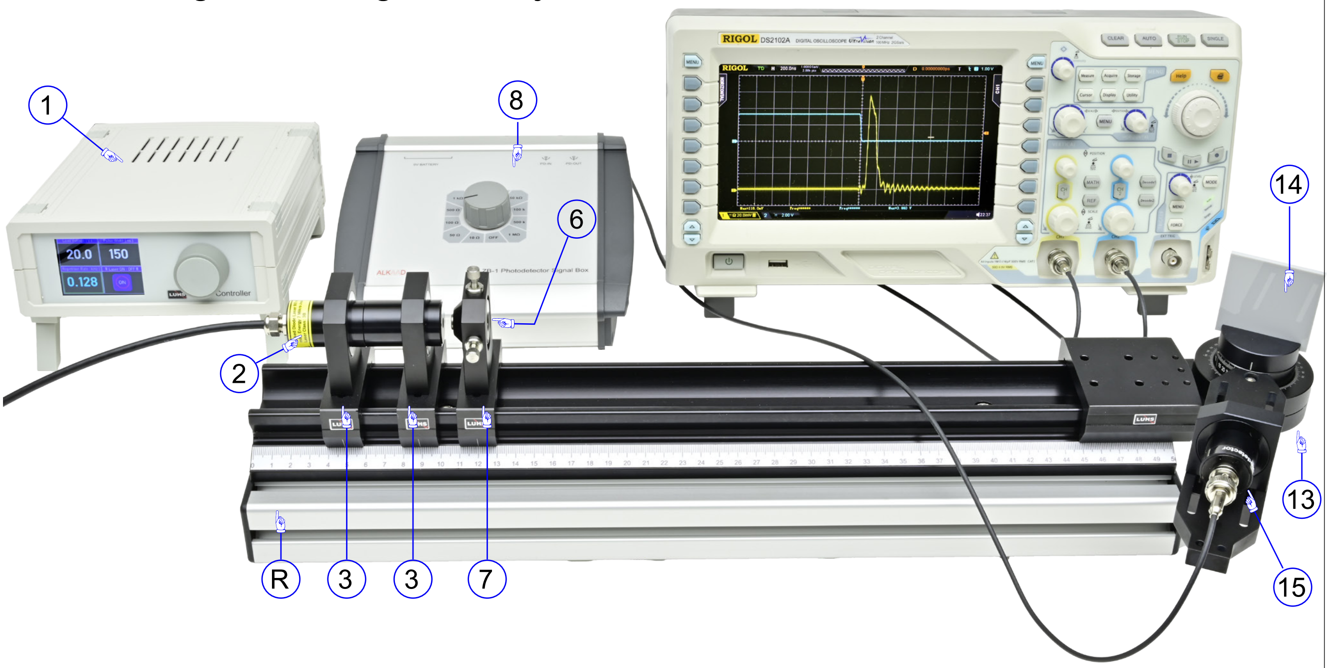


Fig. 25: Measure the scattered light intensity

This section of the experiment involves evaluating the laser radiation scattered on a surface. This is important for determining the MPR value of scattered radiation.

The scattering object (14) is placed in the fixed part of the goniometer. The angle to the optical axis can be read with an accuracy of 1°. Then, the goniometer arm is rotated so that the detector (15)detects the scattered radiation. The scattered laser power is measured at different angles and plotted on a graph (Fig. 26).

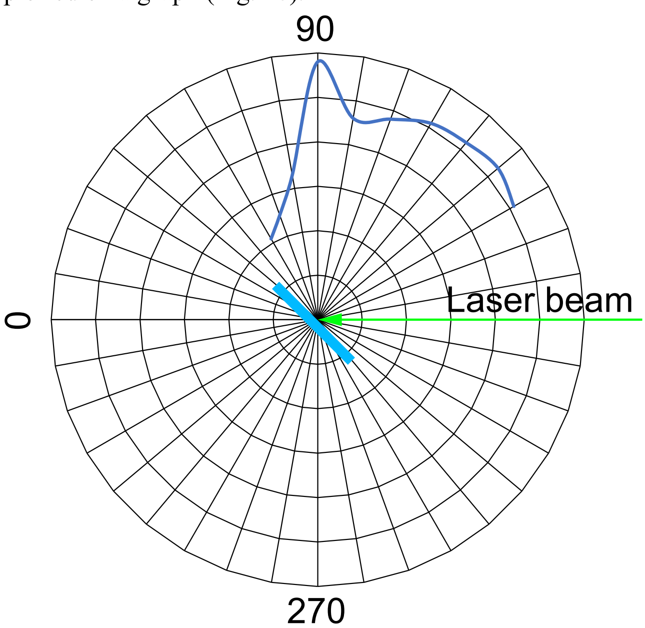


Fig. 26: Example of a measurement, shown in polar coordinates.

Measurements

6.4 *Properties of cw DPSSL*

The following experiments characterize the diode-pumped solid-state laser (DPSSL). First, we measure the laser power. Then, we use two filters to determine the residual content of unwanted near-infrared (NIR) radiation. Knowing the divergence of the laser beam is important to determine the MPR value at any distance. We measure this value with a bi-concave lens that has a known focal length.

6.4.1 Measure the Emission of the DPSSL

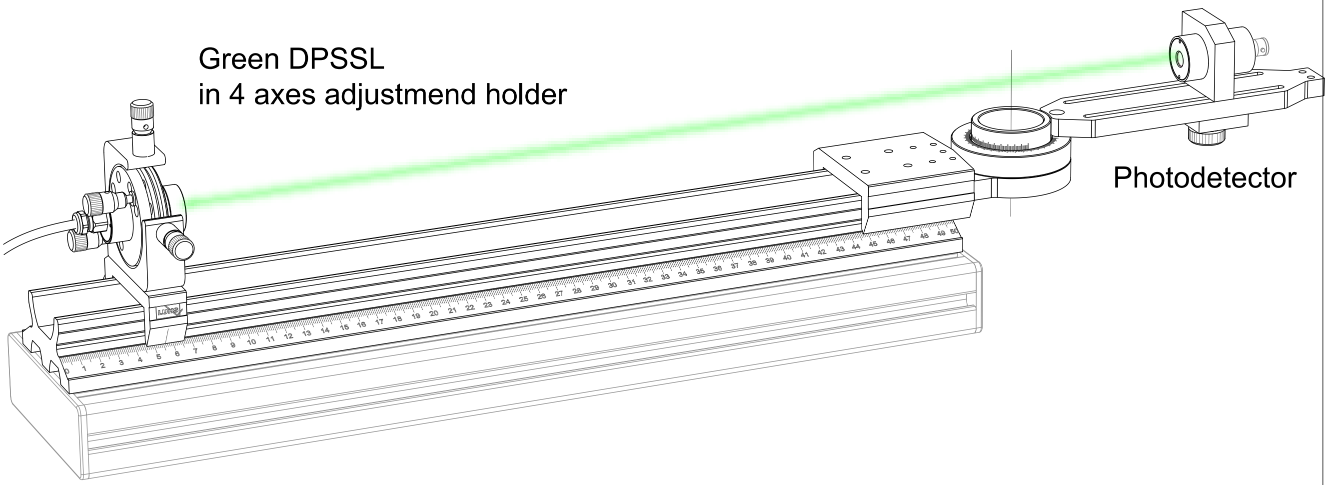


Fig. 27: First step. align the green laser beam to the center of the optical axis

First, we place the DPSSL with the four-axis holder on the optical bench and connect it to the control unit. We select the lowest possible power. The goniometer with the photodetector is set to 0° so that the detector is aligned with the optical axis. Using the adjustment screws on the four-axis holder, we center the green laser beam on the detector surface.

Because the beam covers the detector surface well, we can determine the optical power based on the photodiode‘s photocurrent and its sensitivity curve. The optical power is then calculated using equation (Eq 6). If a calibrated power meter is available, the photodetector can also be calibrated for further measurements.

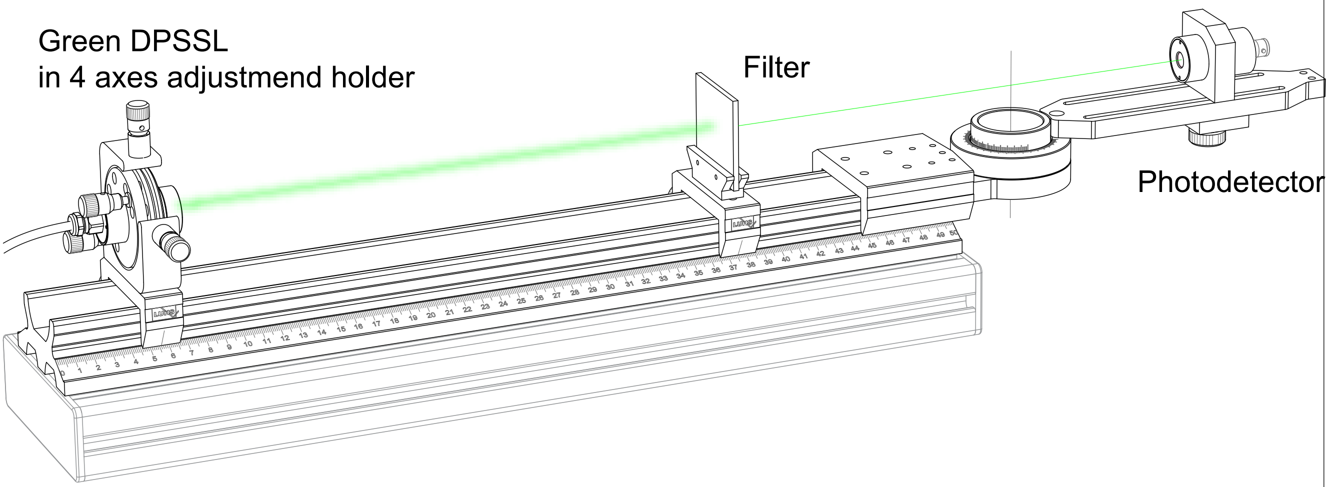


Fig. 28: Measure the output power

As previously mentioned, a standard DPSSL emits unwanted radiation at 808 and 1064 nm, in addition to the desired green radiation at 532 nm.

The BG39 filter blocks nearly all NIR radiation (see the transmission curve Fig. 17), and the OG550 filter blocks nearly all green radiation.

This allows us to measure the optical output power for the frequency-doubled and NIR frequencies separately. The NIR power changes linearly with the pump diode‘s injection current, while we expect the green power to vary quadratically.

Measurements

6.5 Measuring the beam divergence

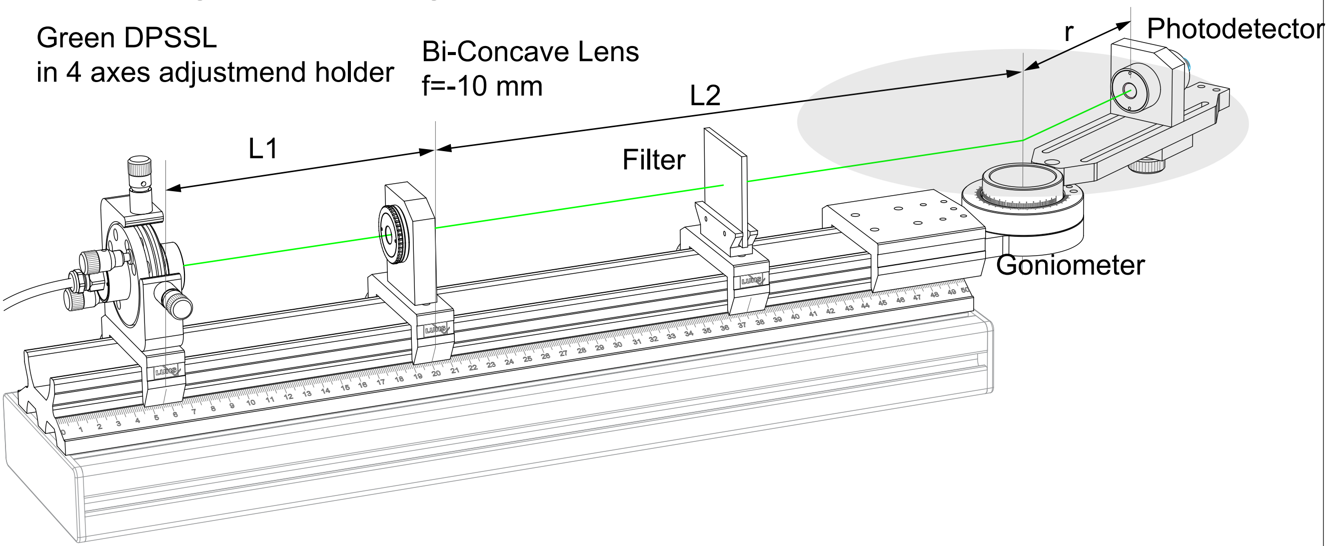


Fig. 29: Arrangement to measure the radial intensity distribution

We will now add the biconcave lens to the previous setup. We set its position a specific distance from the DPSSL and take note of it. To ensure that only green radiation is measured, we insert the BG39 filter. We ensure that the expanded green beam fully penetrates the filter. We connect the photodetector to the connection device, and then connect the output of the device to the digital voltmeter. We switch the digital voltmeter to voltage mode. We select the shunt resistor on the connection box so that sufficient photovoltage is generated without saturating the system. The photovoltage, which is linear to the photocurrent, is recorded as a function of the goniometer angle and displayed as a graph.

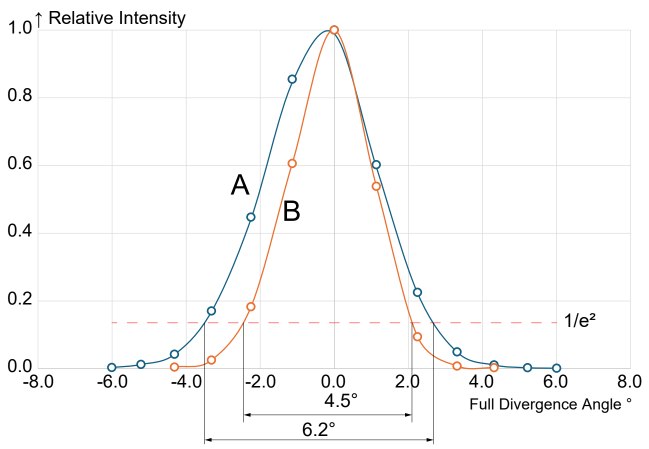


Fig. 30: Two measurements of the radial intensity distribution

Measurements were taken at two distances from L1, 200 and 300 mm. As expected, the intensity distribution corresponded to a Gaussian bell curve. Beam divergence is defined as the point at which the intensity drops to $1/e^2$.

Measurements