Construction and testing of a tunable light source for characterisation of Silicon Photomultipliers

von

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Abstract

This thesis describes the development and construction of a tunable light source which shall be used as test stand for the photo detection efficiency of a silicon photomultiplier (SiPM). Tunable means that in the finished construction it is possible to select visible light of different wavelengths between 400 nm and 800 nm.
The set-up has a main light source whose light is split by either a blazed grating or an equilateral prism, respectively. The spectral light is collected by an optical fibre and coupled into an integrating sphere which is a core element of the readout. In the actual set-up a PIN diode is integrated which later will be used as reference detector. This allows first measurements with the complete set-up. The SiPM to be tested also will be mounted at the integrating sphere. Later a reference light source with four defined wavelengths serves to calibrate the set-up.
First measurements of the photo detection efficiency using the PIN diode provide the expected wavelength spectrum.

Zusammenfassung

Die vorliegende Bachelor-Arbeit beschreibt die Entwicklung und den Aufbau einer durchstimmbaren Lichtquelle, die als Prüfstation für die Photodetektionseffizienz eines Silizium-Photomultipliers (SiPM) genutzt werden soll. Durchstimmbar bedeutet dabei, dass sich im fertigen Aufbau verschiedene Wellenlängen von sichtbarem Licht zwischen 400 nm und 800 nm einstellen lassen.
Der Aufbau hat zunächst eine Hauptlichtquelle, deren Licht mittels eines Blaze-Gitters bzw. eines gleichseitigen Prismas in die Spektralfarben zerlegt wird. Das spektrale Licht wird von einer optischen Faser aufgenommen und in die Ulbricht-Kugel eingekoppelt. Die Ulbricht-Kugel ist ein zentrales Element der Auslese. Dort ist beim aktuellen Aufbau eine PIN-Diode eingebaut, die als Referenzdetektor dient. Auch der zu testende SiPM soll nach Fertigstellung der Lichtquelle in die Ulbrichtkugel eingebaut werden. Eine Referenzlichtquelle mit vier definierten Wellenlängen soll später der Kalibrierung des Aufbaus dienen.
Erste Messungen der Photodetektionseffizienz mit der PIN-Diode liefern die erwartete Verteilung in Abhängigkeit von der Wellenlänge.

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Chapter 1

Introduction

The intention of this thesis is to describe the steps of the construction of a tunable light source, which later shall be used to characterise the light sensitivity of silicon photomultipliers.
The idea of the project is to split up beam of a white light source into it's spectral colours. Therefore at first the construction is tested by using a prism and a blazed grating, respectively. By an optical fibre the white light is lead to a beam splitter where the resulting two beams are guided to the prism and the grating. Behind these optical components the spectral light is coupled into an optical fibre which leads the light to an integrating sphere. In the integrating sphere as reference detector a PIN diode is connected.
The objective is to measure the photo detection efficiency by the light that arrives the silicon photomul-

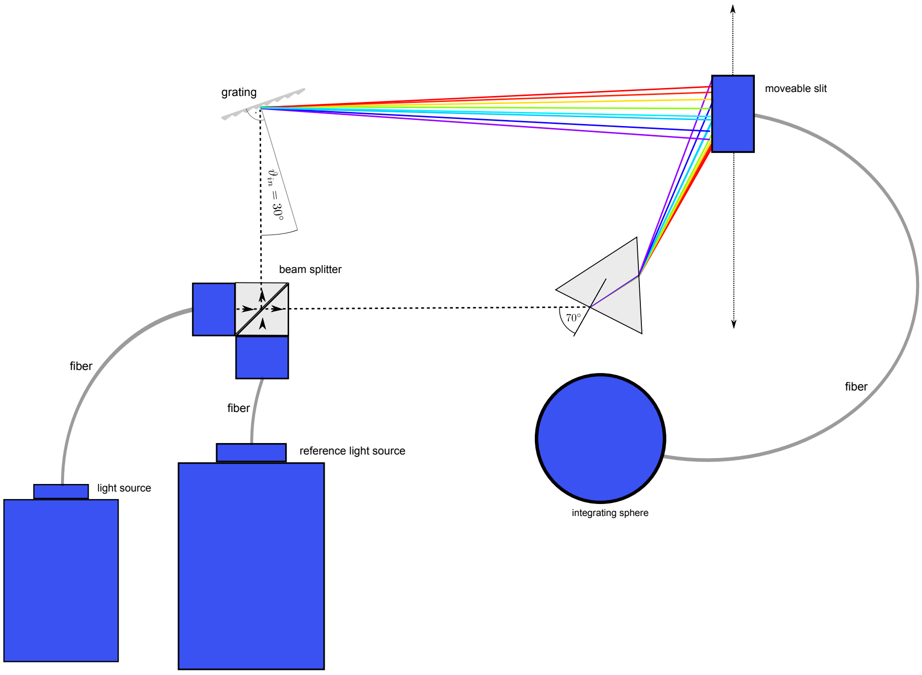


Figure 1.1: Sketch of how the complete set-up will look like.

tiplier in the integrating sphere.
This project was conceived for two students. While this thesis specializes in the practical construction of the test stand, the other concentrates on the theoretical conception (including some simulations) (see [Ric10]).

Chapter 2

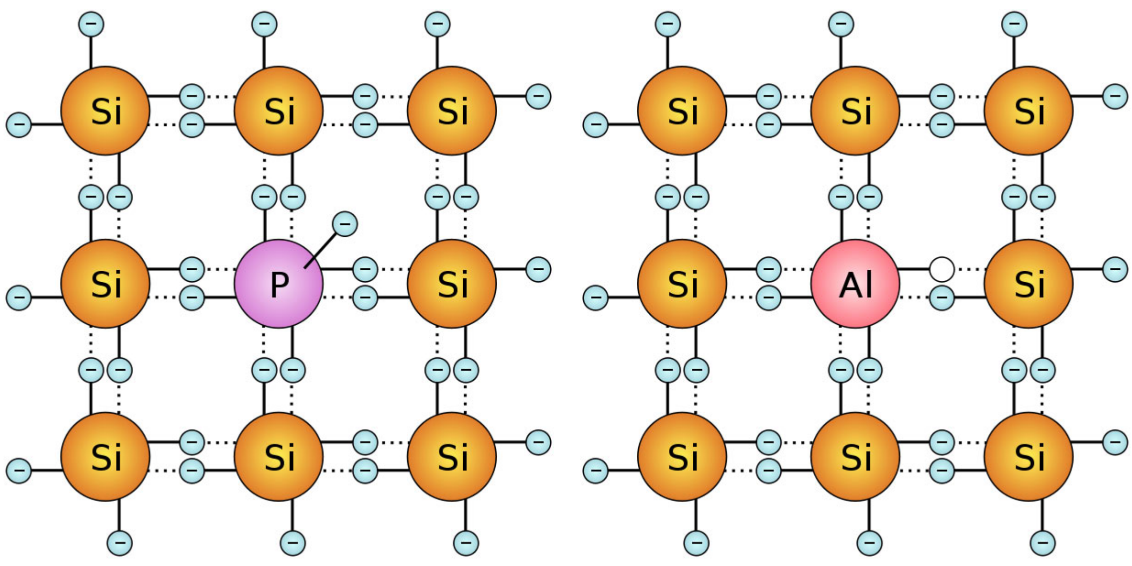
Planning and selection of the components

In the following section the components which are used in the constructed set-up are presented with their physical properties. It is subdivided into the description of the lightsource components and of the reference light source, of the spectral colour dispersion and of the readout components.
The section begins with the description of the diodes which are used for the lightsources.

2.1 Optical Components

2.1.1 Semiconductor light sources

Semiconductors are elements which are bad conductors. By doping these elements they become conductive.
An n-type semiconductor like the group IV element silicon is doped for example with a group V element like phosphorus (donator). Silicon has four valence electrons, phosphorus has five. Both strive to achieve noble gas configuration, that is to have eight valence electrons. So the silicon and phosphorus atoms share their electrons and enter a covalent bond. One electron remains unbound because silicon and phosphorus are from different element groups (see figure 2.1(a)).



(a) Example for an n-type semiconductor [Wik10a]. (b) Example for a p-type semiconductor [Wik10b].

Figure 2.1: Clarification of the doping principle.

These remaining electrons are responsible for the conductivity of the n-doped semiconductor. This is connected with the electronic band structure of a semiconductor.

Light Emitting Diode (LED)

Diodes are semiconductors with a p-n-junction, this means that a p-type and an n-type semiconductor are assembled in close contact. To get a p-type semiconductor, for example group IV elements are doped with group III elements like aluminium. Here movable holes remain (positive charges), which are responsible for the conductivity of a p-type semiconductor.
A light emitting diode (LED) is a p-n-junction which emits light, when the diode is powered in forward direction.
In contrast to a non-luminescent diode, for light emitting diodes combinations of group III and V elements mostly with gallium are used. The electrical properties of a semiconductor are dependent of the size of the band gap.
The possible energy states are arranged to different energetic bands. In termodynamic equilibrium a certain quantity of electrons is in the conduction band, whereas the corresponding quantity of holes is in the valence band at a lower energy (see figure 2.2).

For light emitting diodes semiconductive elements are used which mainly produce radiant changes of

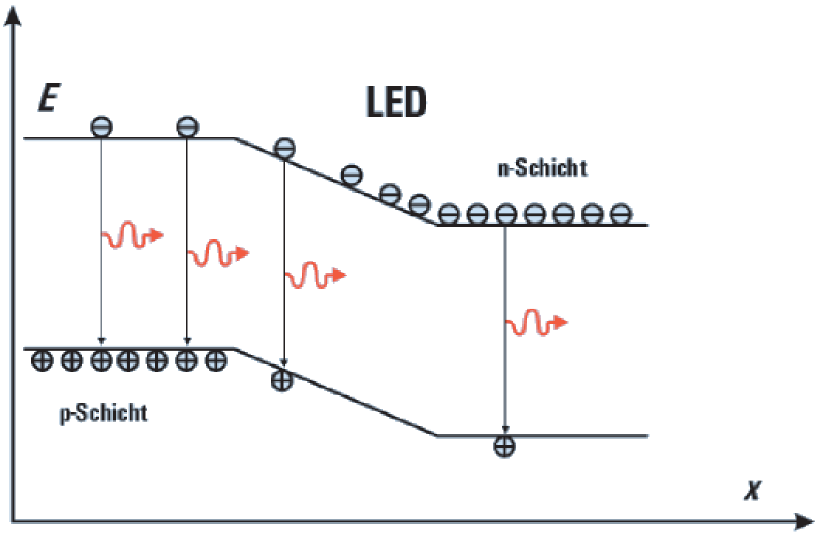
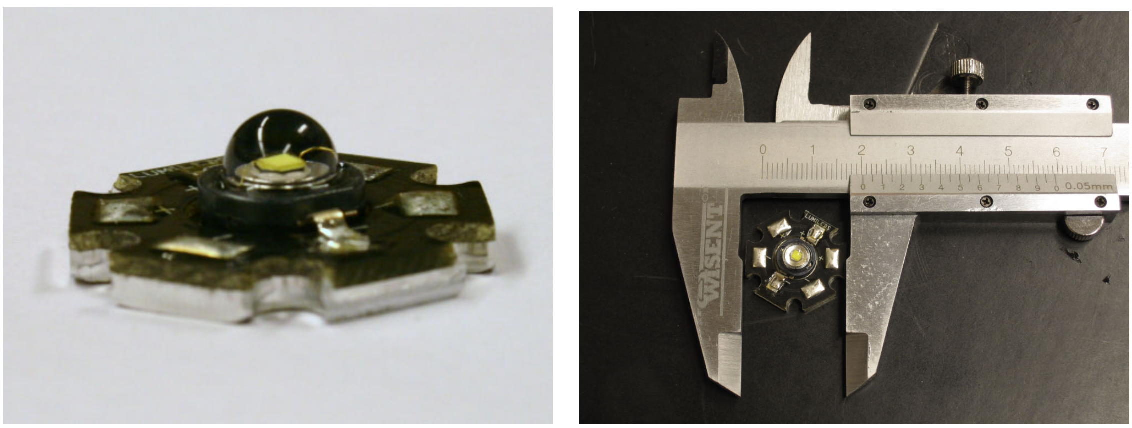


Figure 2.2: Recombination of electrons and holes in an forward biased LED [D.B].

energy levels. The colour or rather the wavelength of the emitted light depends on the width of the band gap. So in general light emitting diodes radiate light of almost one wavelength.



(a) The used LED is mounted on a hexagonal heat sink. (b) Its diameter is about 20 mm

Figure 2.3: As light source we use a LUXEON LED [Lux04].

The used diode (see figure 2.3 and [Lux04]) emits white light, all wavelengths of light are distributed over a spectrum between 400 nm and 700 nm. For white LEDs blue or UV emitting diodes which are combined with luminescent phosphorus are used. The high-energy blue light excites the phosphorus, that emits lower energetic light about the whole spectrum.

Laser diodes

The function of laser diodes is similar to simple LEDs but the emitted light has laser characteristics.
Four laser diodes of different wavelengths are used for the reference light source. There are built in a blue (405 nm) , a green (532 nm) and two red laser diodes (635 nm, see appendix fig. A.1, and 670 nm, fig. A.2).
To get an as collimated beam as possible for these laser diodes special collimators are used (see fig. 2.4).

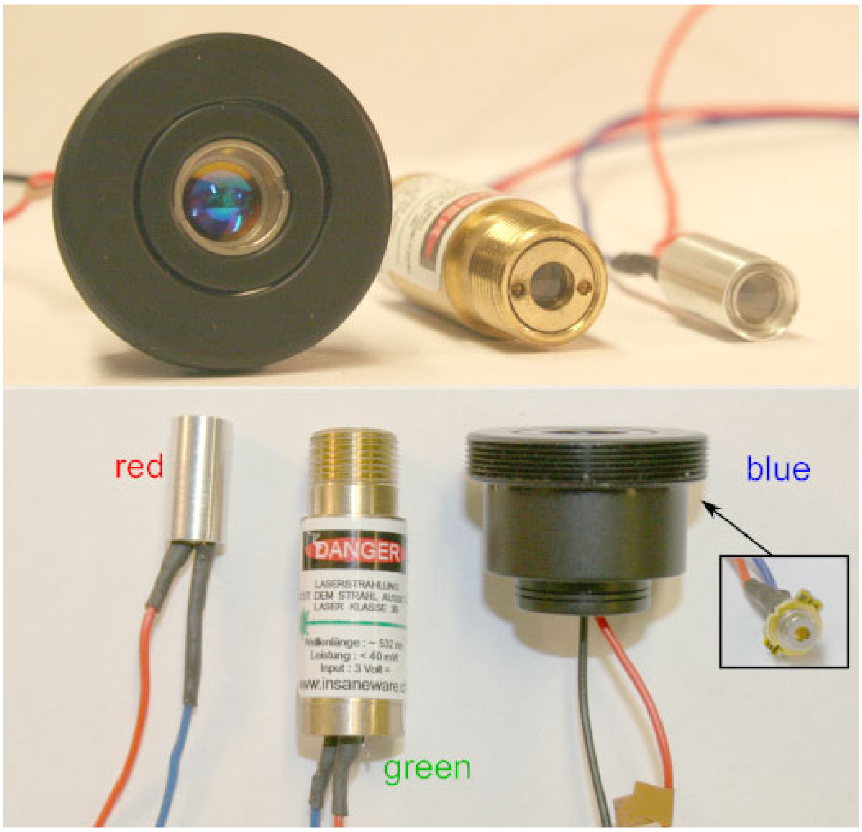


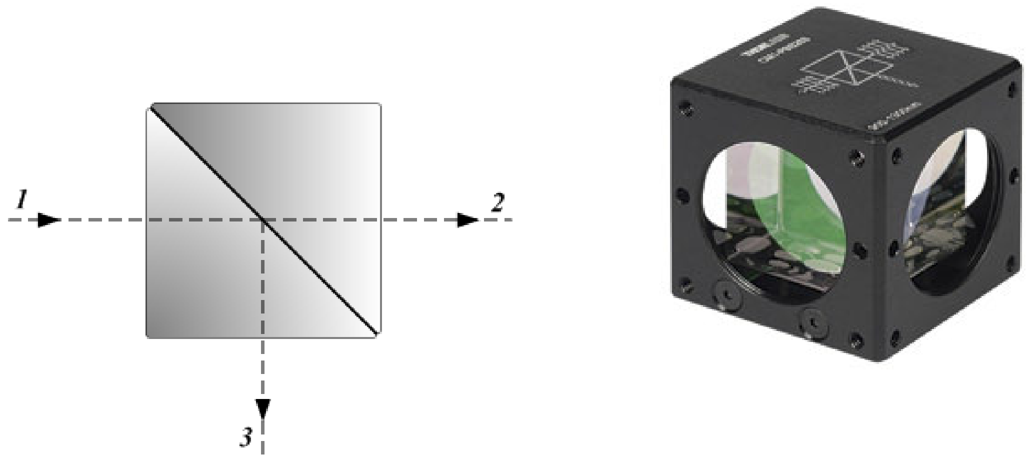
Figure 2.4: All used laser diodes have a special collimator.

The red diodes are already integrated into optimized collimators. The blue diode also is mounted inside an optimized collimator, the adjustment has to happen manually (see section 3.2). The green laser diode was originally a laser pointer so that the light is already collimated.

2.1.2 Beam splitter

Beam splitters are used to combine the beams of the laser diodes in the reference light source and later the beam of the primary light source with the beam of the reference light source.
A beam splitter consists of two right angled prisms which are stuck together at their base by an optical glue, that has another refractive index than the two prisms. Optical glue has optical properties which are simliar to the ones of glass. The refractive indices of the glass and the glue have to be different so that the beam can be split by reflections and transmissions (see figure 2.5(a)).

In general the distribution of intensity of the two beams depends on the refractive indices of the prisms and the optical glue. When the beam reaches the surface of the used cube in an angle of $0°$ to the surface normal 50% of the beam are transmitted through the glass and 50% are totally reflected.
In the present construction two different beam splitters are used. The bigger one is used as permanent and independent component in the construction. It is fixed in an anodized cube which can be mounted in the set-up (see appendix fig. A.3). The three smaller beam splitters (see appendix fig. A.4) are used for the construction of the custom designed reference light source (see section 3.2). For the three smaller beam splitters the manufacturer provides information about the sort of glass. These beam splitters consist of



(a) (b)

Figure 2.5: left: schematic depiction of a beamsplitter - 1: incident light 2: transmitted light 3: reflected light. - right: Catalogue picture of the used beam splitter cube [Tho10c].

BK7-glass. This type of glass is typical for optical glass components because its refractive index is about 1.5.

2.1.3 Optical fibre

At two different points of the test rig optical fibers are used to transport light. The transport of light is an often used application of the total internal reflection. It is possible to transport light with small loss of intensity. The simplest type of an optical fibre is a glass or synthetic rod in which total reflection happens at the interface from glass to air. Generally there is an additional cladding around the glass, which replaces the air. To enable total internal reflection the refractive index of this cladding has to be smaller than the one of the fibre's core. Using the two refractivities it is possible to calculate the critical angle of the total internal reflection .

Total internal reflection occurs for all angles of incidence that are bigger than the critical angle α_c. This leads to the accepting angle, which is the maximum incident angle to the fibre, at which total reflection inside the fibre happens. As long as the diameter of the fibre is large against the wavelength of the incoming light, the wave characteristics have a subordinate significance and the geometrical optics can be used to describe the phenomenon of total internal reflection.
For total reflection the exit angle β is at least 90° (see figure 2.6).

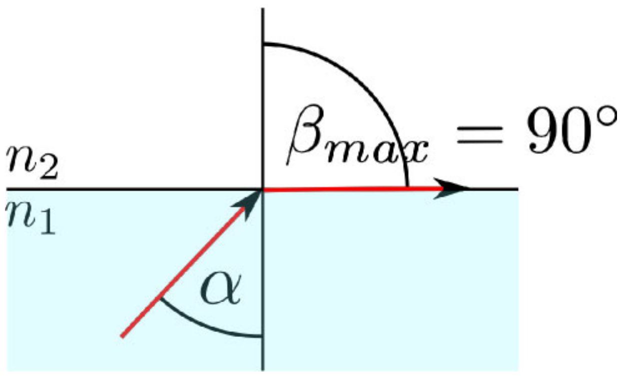


Figure 2.6: The critical angle α_C of total internal reflection belongs to $\beta = 90°$.

Here optical fibers with a diameter of 0.55 mm and 0.2 mm are used. Both have a numerical aperture

of 0.22 and their spectral range lies between 350 nm and about 2000 nm, their length is 1 m.
The numerical aperture indicates the maximum angle up to that the incident light is coupled into the fibre. With Snell's law the critical value α_C of the incident angle and consequently the numercial aperture can be calculated. In the following considerations n_1 is the refractivity of the core and n_2 of the cladding.

$$\begin{aligned} n_1 \cdot \sin(\alpha) &= n_2 \cdot \sin(\beta) \text{ (Snell's law)} \\ \arcsin\left(\frac{n_1}{n_2} \cdot \sin(\alpha)\right) &\geq \frac{\pi}{2} \\ \alpha &\geq \arcsin\left(\frac{n_2}{n_1}\right) \\ \Rightarrow \alpha_C &= \arcsin\left(\frac{n_2}{n_1}\right) \end{aligned}$$

The critical angle is the minimal angle at which total internal reflection happens. Now it is possible to calculate the maximum incident angle ϑ_i of the beam that arrives the surface of the fibre (see figure 2.7). This angle will lead us to the numerical aperture (NA) of the optical fibre.

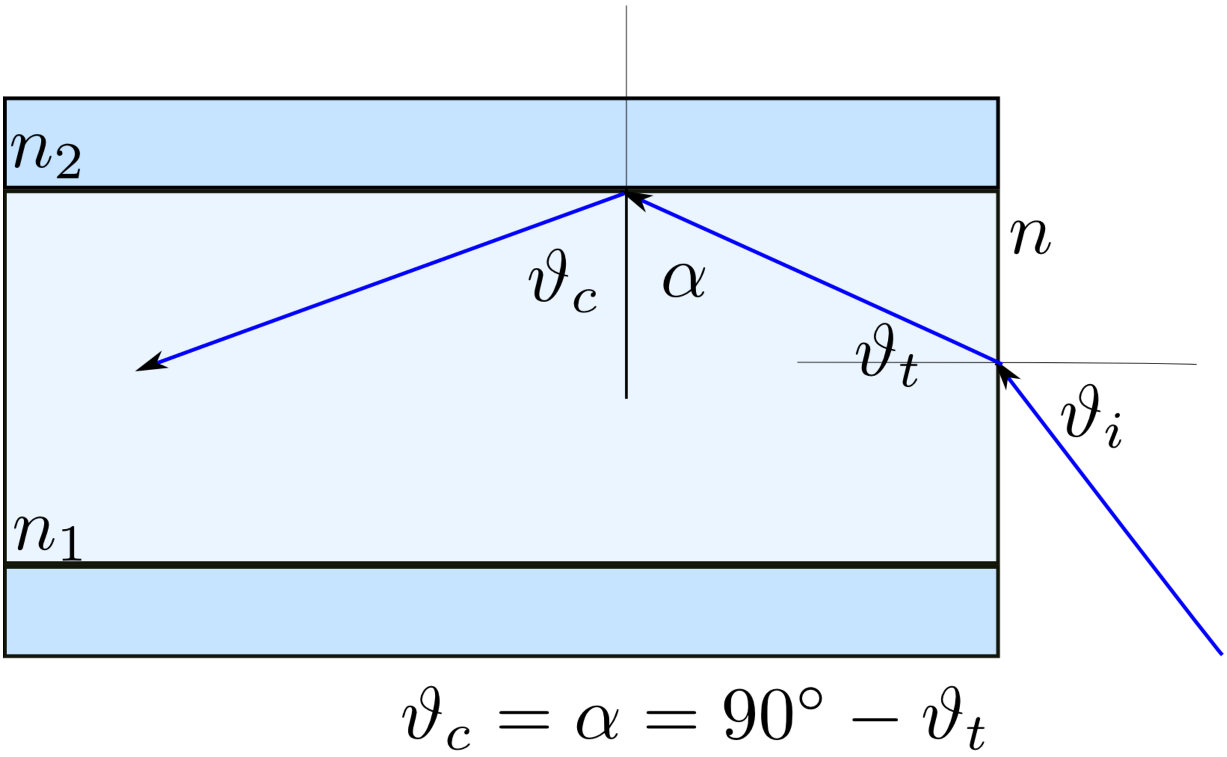


Figure 2.7: The NA depends on the maximum incident angle ϑ_i.

$$
\begin{aligned}
n \cdot \sin\vartheta_i &= n_1 \sin\vartheta_t \\
\vartheta_t &= \arcsin\left(\frac{n}{n_1} \cdot \sin\vartheta_i\right) \\
\alpha = 90^\circ - \vartheta_t \Rightarrow 90^\circ - \alpha &= \arcsin\left(\frac{n}{n_1} \cdot \sin\vartheta_i\right)
\end{aligned}
$$

critical angle of total internal reflection:

$$
\begin{aligned}
\sin\alpha \geq \frac{n_2}{n_1} \Rightarrow \alpha &\geq \arcsin\left(\frac{n_2}{n_1}\right) \\
\Rightarrow 90^\circ - \arcsin\left(\frac{n}{n_1} \cdot \sin\theta_i\right) &\geq \arcsin\left(\frac{n_2}{n_1}\right) \\
\frac{n}{n_1} \cdot \sin\vartheta_i &\leq \cos\left(\arcsin\left(\frac{n_2}{n_1}\right)\right)
\end{aligned}
$$

Using the following addition theorem:

$$
\begin{aligned}
\cos(\arcsin(x)) &= \sqrt{1 - x^2} \\
\Rightarrow \vartheta_i &\leq \arcsin\left(\frac{1}{n}\sqrt{n_1^2 - n_2^2}\right) \\
\Rightarrow \sin\vartheta_{imax} &= \frac{1}{n}\sqrt{(n_1^2 - n_2^2)}
\end{aligned}
$$

The numerical aperture (NA) is defined as $NA = n \cdot \sin\vartheta_{max}$. Thus we find:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{2.1}$$

Using $n \approx 1$ (refractive index of air) we get

$$NA = \sin\vartheta_{max}. \tag{2.2}$$

So the NA is a measure for the maximum incident angle of the incoming and the outgoing light. For more information about fibres and their numerical aperture see the chapter about fibreoptics in [Hec87].

In the present project two optical fibres with different diameter are used. The smaller one is better to focus the beam of light, because it describes a better approximation for a point source. The fibre with the larger diameter is used to couple the spectral light into the integrating sphere. With that it is possible to get beams of higher intensity. Because of it's larger diameter it leads more photons to the integrating sphere and consequently to the silicon photomultiplier (see chapter 3).

2.1.4 Lenses

The set-up for the tunable light-source utilizes different lenses which have different tasks. On the one hand the light which comes from the white LED is focused by a condenser (two plano-convex lenses, see fig. 2.8) to optimize the coupling into the optical fibre. It should be optimally adjusted when

$$\frac{d}{S} = \frac{f_L}{f_C} \tag{2.3}$$

is fulfilled. In the present set-up there are $d = 0.2mm$, $S = 1mm$, $f_L = 25mm$ and $f_C = 35mm$. Later we will see, that these measures are not compatible (see section 3.1).

On the other hand, after leaving the fibre, the light has to be collimated. This will be done by an aspheric lens.

The aspheric lenses are adapted to the numerical aperture of the optical fibre and to light of 633 nm wavelength. They have a diameter of 7.2 mm and are made of NBK-7 glass. Because they are uncoated lenses they are also usable for the important wavelengths between 350 nm and 800 nm. Their effective focal point is at 11 mm. In the collimator for the blue laser diode there is a coated to loose less intensity. This coating with a spectral range between 400 nm and 700 nm reduces the reflections, which would evoke loss of intensity. The reflexions are reduced by destructive interference. Without the anti-reflective coating about 4% of intensity would be lost at each interface between glass and air [Gri09].

The lenses are aspheric to reduce the effect of spherical aberration. Additionally spheric and uncoated lenses are used because these ones are not adjusted to specified wavelengths. Therefore these lenses are more flexibly applicable. With an adaptor they are mounted in the 1" tube system.

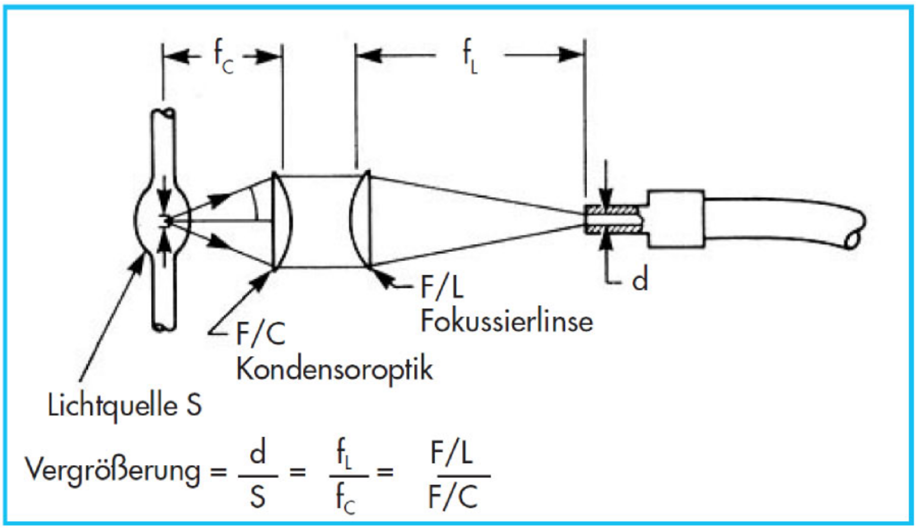


Figure 2.8: The light is focused by a condenser that consists of two plano-convex lenses [Eur10].

2.1.5 Spectral colour dispersion

The spectral colour dispersion is done by one prism and by a blazed grating, respectively. It is tested, which component is more suitable for the present set-up.

Using a prism

A prism is an optical glass component which has a triangle as base area. It's optical properties basically depend on the angles of this triangle and of the refractive index of the used glass. A prism can split white light into it's spectral colours by dispersion. Dispersion is the phenomenon that light of different wavelengths experiences different refractive indices and therefore different velocities in the same medium. This is the cause for the splitting into the spectral colours. For the present project we use an equilateral prism with $\gamma = 60°$ and a baselength $b = 2$ cm.

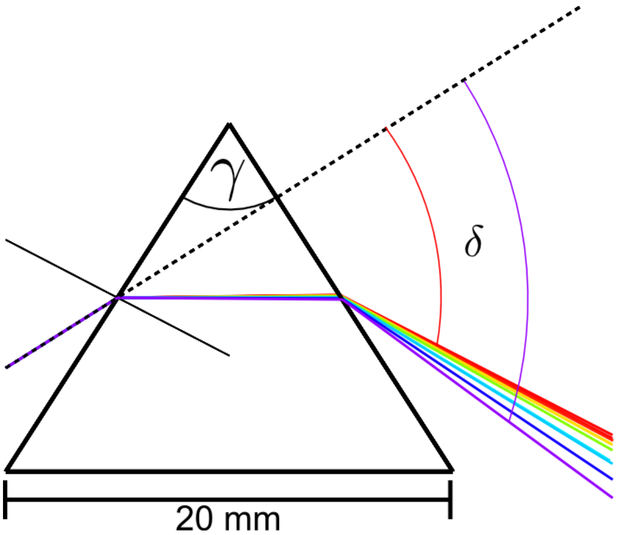


Figure 2.9: The deflexion angle δ is maximized by selecting a prism with a large refractity.

The used prisms are made of N-SF11 glass (see appendix fig. A.5), that also is an often used material for optical components. Compared with BK7-glass which is used for the beam-splitters, N-SF11 is more sensitive to touch and stains easily. To remain it's optical qualities it has to be treated carefully (with gloves) or respectively cleaned off quickly from fingerprints(see appendix fig. A.7). Moreover it has a larger refractive index than BK7-glass. The prism with a large refractive index is chosen to achieve a maximum difference between the deflexion angles δ (see figure 2.9) of red and blue light with the aim to heighten the precision reading out the spectrum.

Plotting the refractive index n of N-SF11 and N-BK7 glass against the wavelength λ (see fig. 2.10) one

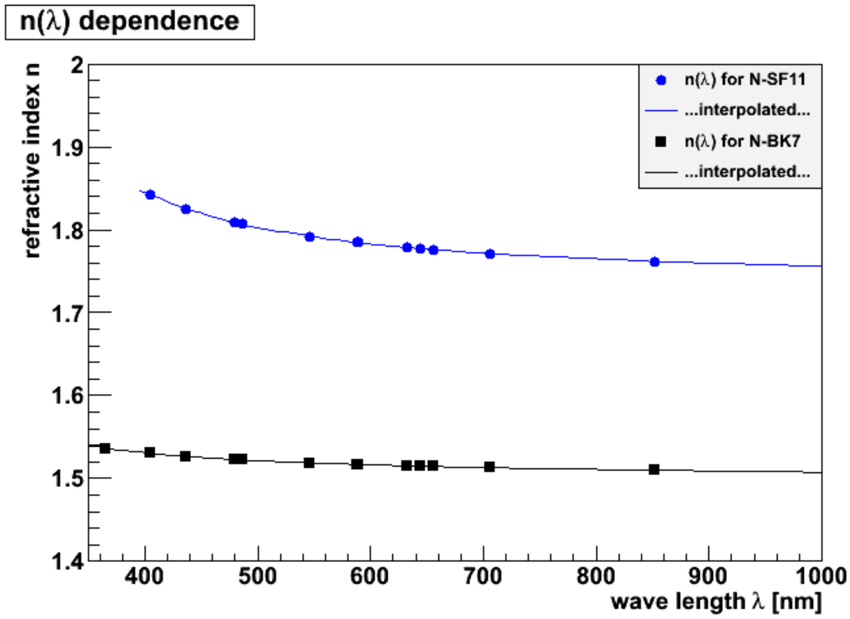


Figure 2.10: The refractive index of N-SF11 glass is larger than the one of N-BK7 glass.

sees at once that the refractivity of N-SF11 is clearly larger than the one of N-BK7 glass. Moreover the interpolated function of the N-SF11 refractivities has a larger slope what shows that the difference between the refractive indices of red and blue light is larger than with N-BK7 glass. This leads to the desired effect that the spectrum is split up maximally. In the set-up the prism is fixed on a kinematic platform (see appendix A.6) for prism which is mounted on a rotatable plate (see figure 2.11). There is a degree scale which makes it possible to adjust the calculated angle at which the light beam has to hit the surface of the prism. There is a 2°-scale which makes an adjusting precision of more or less $\pm 0.5°$ reachable.

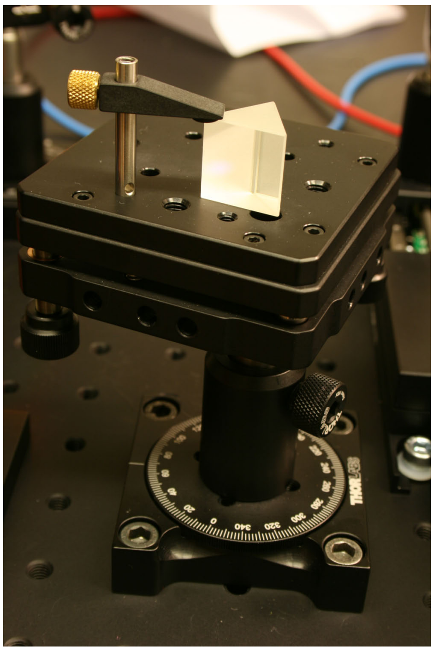


Figure 2.11: The prism is mounted on a rotatable table to adjust the incident angle.

Using a blazed grating

The reflective blazed grating is used as second component to split up the white light into its spectral colours. In most cases of spectral analysis prisms were replaced with gratings (see figure 2.12).

The blazed grating's surface has facets (grooves), which evoke the spectral colour dispersion by interfer-

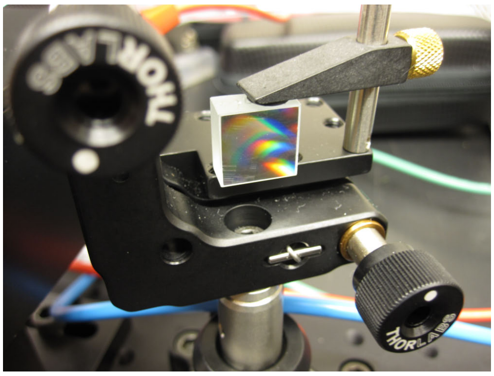


Figure 2.12: Ruled Diffraction Grating, 600/mm, 500 nm Blaze, 12.7 x 12.7 x 6 mm

ence and diffraction of light (see figure 2.13). Furthermore it is coated with a reflecting material.

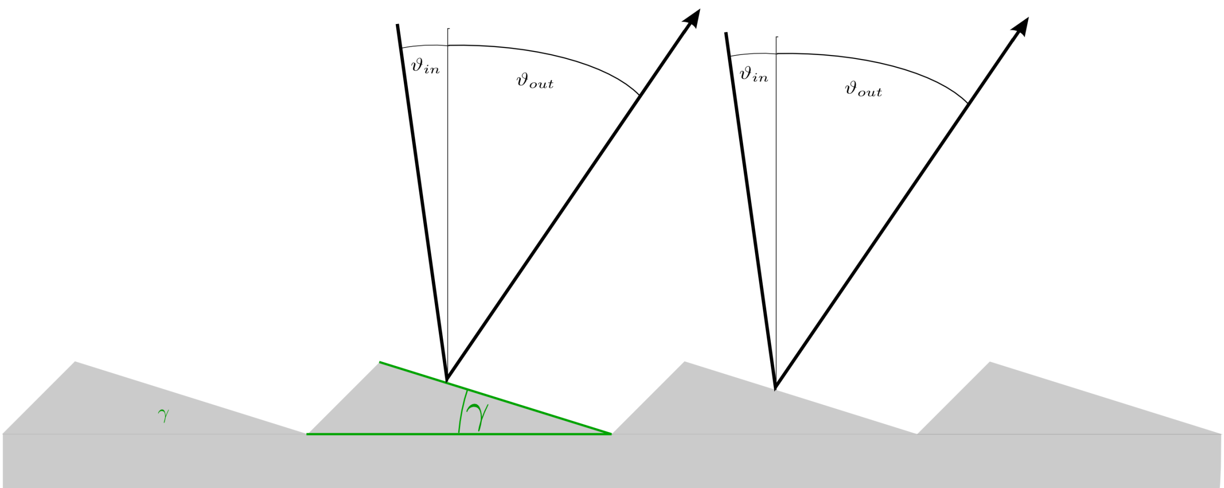


Figure 2.13: Spectral colour dispersion by a blazed grating [Ric10].

A blazed grating is optimized for a special wavelength. At this wavelength the grating produces maximum intensity. The blaze wavelength of the selected grating is at 500 nm. This corresponds to green light, which is situated more or less in the middle of the appearing spectrum so that the calculations can approximately also be applied to the other wavelengths of the spectrum. Moreover the used grating has a blazing angle γ of $8°37'$ and 600 lines per mm which lead to a constant distance between the grating lines of 1.6 µm. Like the prism also the blazed grating is fixed to an kinematic mount which is assembled on a rotatable platform with a degree scaling to adjust the incident angle (see figure 2.14). The specifications of this scaling are the same as for the prism.

For further information about optics see [Hec87], [Ped96] and [Sch07].

2.2 The readout components

2.2.1 Motorised Stage

The motorised stage (see appendix fig. A.12) is the element of the set-up that makes it possible to select different wavelengths electronically. It is movable in one direction (see fig. 2.15) and the optical fibre is mounted on the track. The control can happen manually but using Windows it is also possible to program it. The aim is to program it so as to pass the program the desired wavelength and the motor driver leads the fibre to the corresponding point in the spectrum. Due to missing drivers for Linux it could not be integrated into our lab software so far.

For the first measurements it is sufficient to use the two buttons on the control element to move the motor driver (see manual [Tho]). There are two "move/jog" buttons two move the motor driver step by

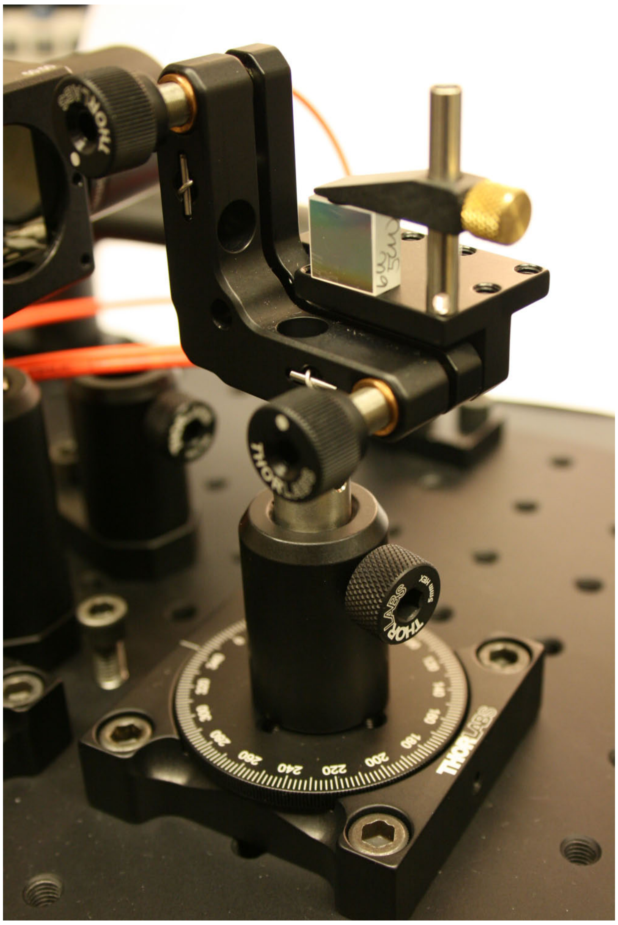


Figure 2.14: The blazed grating is mounted on a rotatable table.

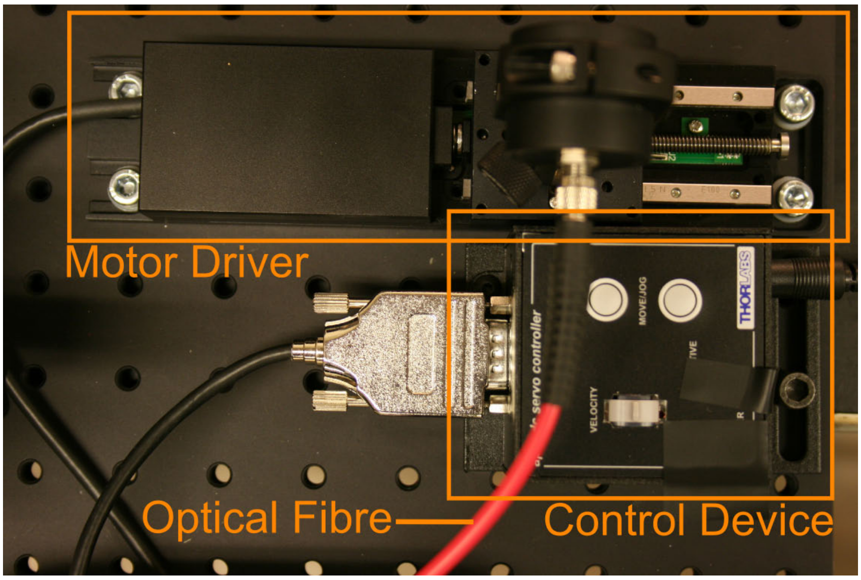
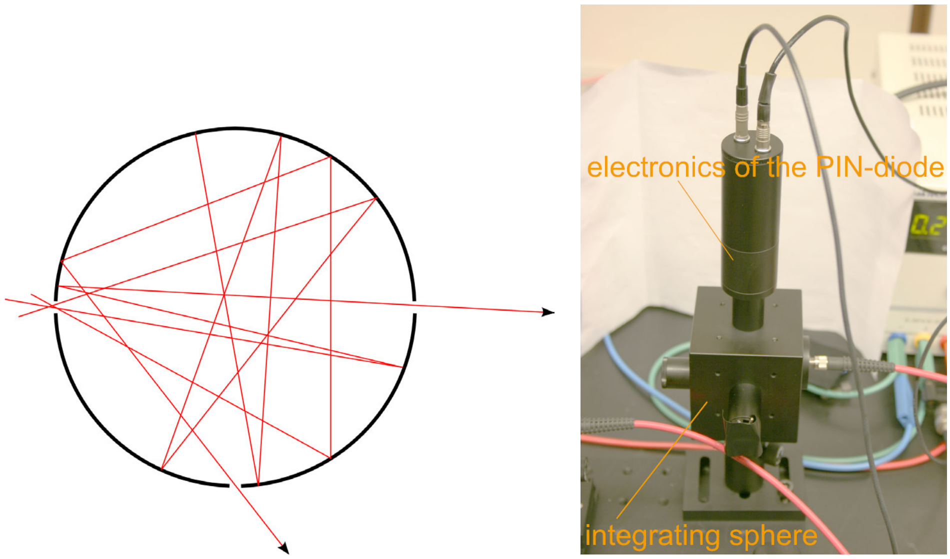


Figure 2.15: The motor driver in the set-up.

step forward and reverse. Using the “move/jog” button the track can cover 50 steps on the complete path of 50 mm, so that each step has a width of 0.5 mm. Every position is repeatable with an acurracy of 2 µm. It is powered with a voltage between ±10 V and ±12 V. All important information about the motorized stage can be gathered from the accompanying manual (see [Tho10b]).

2.2.2 Integrating Sphere

From the motor driver the spectral light is lead to the integrating sphere by an optical fibre. The integrating sphere is a spherical cavity, where the incoming light is reflected diffusely (see figure 2.16(a)). This is important for the testing of the silicon photomultiplier because it enables that the light arrives it from all directions and that everywhere is the same intensity per area. This cavity has three openings. In one of



(a) Inside the integrating sphere the light is reflected diffusely [Ric10].

(b) In the first measurements the set-up is tested by a PIN diode.

Figure 2.16: The integrating sphere is important for the measurements with the detectors.

them the light of the optical fibre is coupled into the cavity. In the two others are integrated the silicon photomultiplier and a PIN diode as reference detector, respectively to measure the photo efficiency. The SiPM was not present in our set-up.
For the first testings the current of the PIN diode is measured in dependence of the position of the optical fibre in the spectrum. It is possible to measure a current in the PIN diode in dependence of the energy or rather the wavelength of the incoming light. The quantum efficiency of the used PIN diode is shown in figure 2.17. This shows that the quantum efficiency of the used PIN diode has its maximum values between

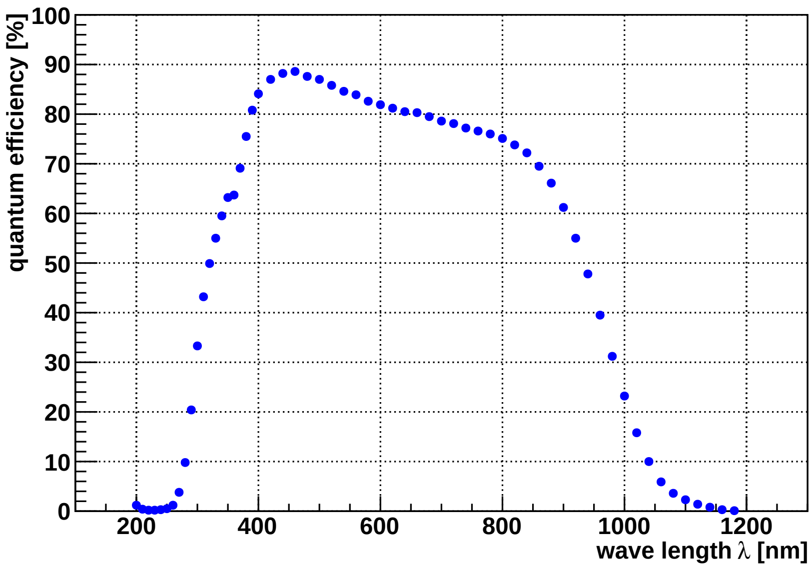


Figure 2.17: The quantum efficiency has its maximum between 400 nm and 500 nm

wavelengths of 400 nm and 800 nm. In this area between 90 percent and 75 percent of the incident light

produces a signal in the diode. The PIN diode has an active area of 5 mm×5 mm.
More information about measurements with SiPM and integrating sphere and characterisation of PIN diodes can be found in the bachelor thesis from Jan Schulte (see [Sch10b]).

Chapter 3

Construction

3.1 Construction of the main light source

The light source is custom designed (see figure 3.1). The main element is the white high power LED with a power of 3 W and a maximal current of 700 mA (see [Lux04]). It is powered using an DC-current source (see appendix figure A.8) which can provide a current up to 700 mA specially for a high power LED. When the LED is powered it can get very hot and this can damage it. To avoid overheating it is mounted on a brass block, which is a good heat conductor. To increase the thermal conductivity of the interface between the diode and the brass block, the diode is stuck on it with a thermal paste.

In front of the diode there is mounted a to couple the maximum intensity into the fibre by collimating

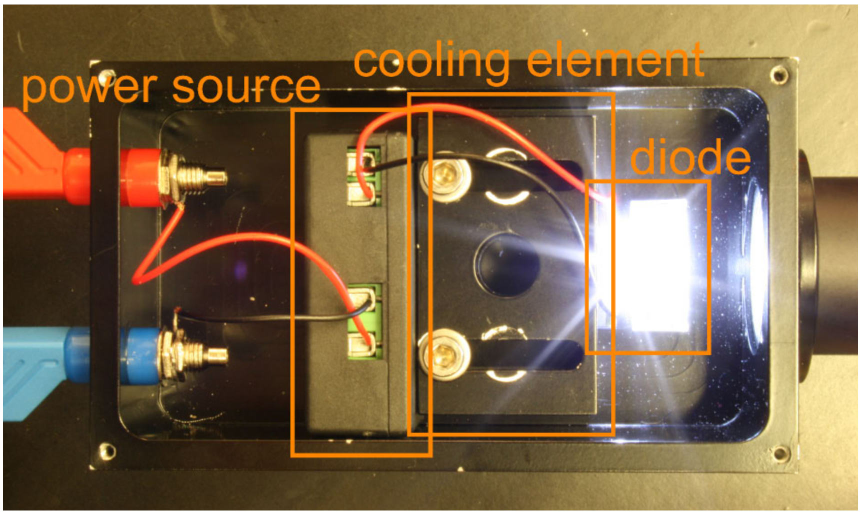


Figure 3.1: The main light source has a custom designed set-up.

the light. The condenser consists of two plano-convex lenses (see fig. 3.2) which are mounted inside an optical tube system with a diameter of 1". The positions where the lenses have to be placed could be calculated and depend on the focal lengths of the used lenses, respectively, but it turns for the best to try out these positions. Therefor the current in the PIN diode is measured and tried to be maximized. The finished setup is shown in figure 3.2. Between the two lenses there is a variable thread which serves for the adjusting of the distance between the lenses to maximize the measured current in the PIN-diode. The optical fibre is placed 7 mm before the end of the tube. With the equation 2.3 we see:

$$\frac{d}{S} = \frac{0.2\text{mm}}{1\text{mm}} = 0.2 \neq 0.7 \approx \frac{25\text{mm}}{35\text{mm}} = \frac{f_L}{f_C} \quad (3.1)$$

So the used components are not optimally compatible but with the chosen adjustments it is possible to get an acceptable result. At the maximum possible current the settings should be as optimized as possible. With the fibre with a diameter of 550 µm there is measured a current of about 2400 nA and with the smaller fibre (200 µm) there are measured 370 nA. Although the larger fibre provides a higher intensity, it is necessary to use the smaller fibre to get a better collimation.

For the different aims (focusing and collimation) the lenses are placed in a different order. If the light

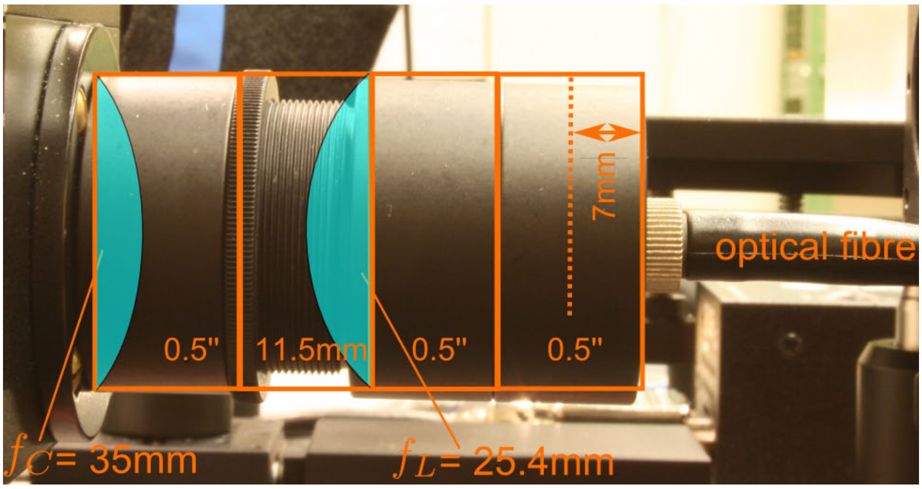


Figure 3.2: The light is focused into the fibre by a adjusted condenser.

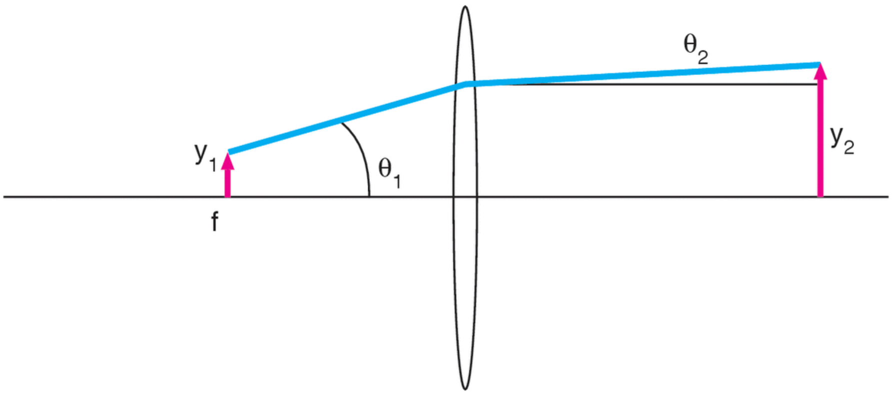


Figure 3.3: Collimation of an extended light source is not possible, there remains a rest divergence [New10].

source were an ideal point source, it had to be placed in the focal point of the lens on the planar side of the lens to be collimated. Real light sources are indeed no ideal point sources. Therefore the light cannot be collimated placing the light source in the focal point of the lens. A better collimation can be achieved when the light source is put at a shorter distance in front of the lens. At the right distance can more or less be pretended that there is a point source with the emission angle θ_1. The beam is nearly collimated but there remains a divergence θ_2 (see figure 3.3). After leaving the light source fibre a collimated beam of light is demanded. To reduce the problem of the not ideal point source, at this point it is better to use the smaller fibre although there is more loss of intensity than with the larger one. This is also gets clear trying the different fibres in the set-up. Here is used one aspherical lens which is adapted to the properties of the used fibre (see section 2.1.4). Without the collimating lens the beam that comes out of the fibre has a divergence $\theta_1 = 0.220$ rad (NA) (see fig. 3.3). After collimating the beam of light, we can measure a rest divergence $\theta_2 = 0.008$ rad.
For focusing the light beam has to be parallel. Because none of the used light beams is ideally parallel it is not possible to focus the light in an ideal point. Collimating the beam by a first lens, it is possible to focus it better with a second lens. The focusing is done to couple as much as possible of the diode light into the fibre. Such a construction is called condenser.
All the components are built into an aluminium box with a non reflecting black paintwork. In an optical set-up it is important to avoid reflections which could evoke interference in the measurements.

3.2 Reference light source

3.2.1 Construction of the reference light source

The reference light source has a beam of light that includes light of four defined wavelengths: 405 nm, 532 nm, 635 nm and 670 nm. The light of it will also pass the prism and the grating respectively. The task of this additional light source is to characterize four fixed points in the spectrum. The measured spectrum can then be compared with the reference light and the calculations can be verified.
These wavelengths come from the four laser diodes which are integrated in the light source. They are superimposed by three beam splitter cubes. Like for the main light source all components are put up in a non reflecting black varnished box.

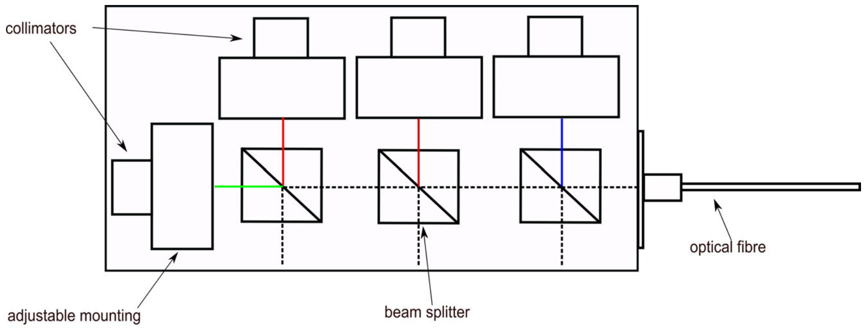


Figure 3.4: In the reference light source four laser diodes are brought together.

Each laser diode has its own collimator. Generally laser diodes are better collimated than simple diodes. Anyway it is necessary to collimate them.
Unfortunately it was not possible to finish the construction of this light source. When the set-up of the reference light source is accomplished it should be examined if it is useful to attach an additional collimation lens in front of the beam which contains the light of all three diodes.

Besides the mentioned components there are also some calibration elements in the reference light source box. The laser diodes are mounted in fixtures which can be adjusted in direction of x, y and z. One part of this fixtures is a kinematic mount (see appendix figure A.11).
These adjusting elements are necessary because the four laser diodes have to be adjusted in such way that at the output of the box they are all combined in one beam. Therefore they have to be brought into one line. The beam splitter cubes are also adjustable because they have to be parallel and aligned to the same point.

3.2.2 Electrical power supply of the laser diodes

The silicon photomultiplier to be tested is not resistant to high photo fluxes so the light has to be pulsed to test the photomultiplier with it. It is not that easy to construct a pulsed current source for the used laser diodes. Therefor in the first measurements the light source is tested with the PIN diode instead the silicon photomultiplier. Here a continuous power source for the diodes can be used but anyhow there has to be integrated a current limiting. Without the current limiting the diodes could get to much current and overheat.

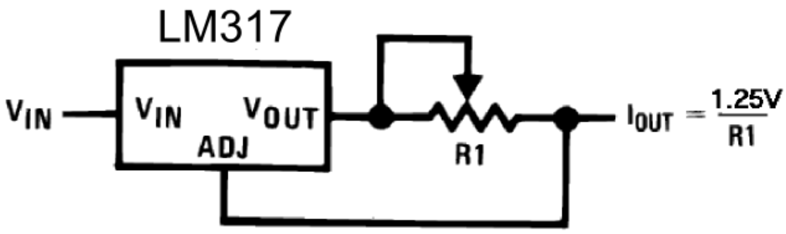


Figure 3.5: Foundation for the constructed circuit [www10].

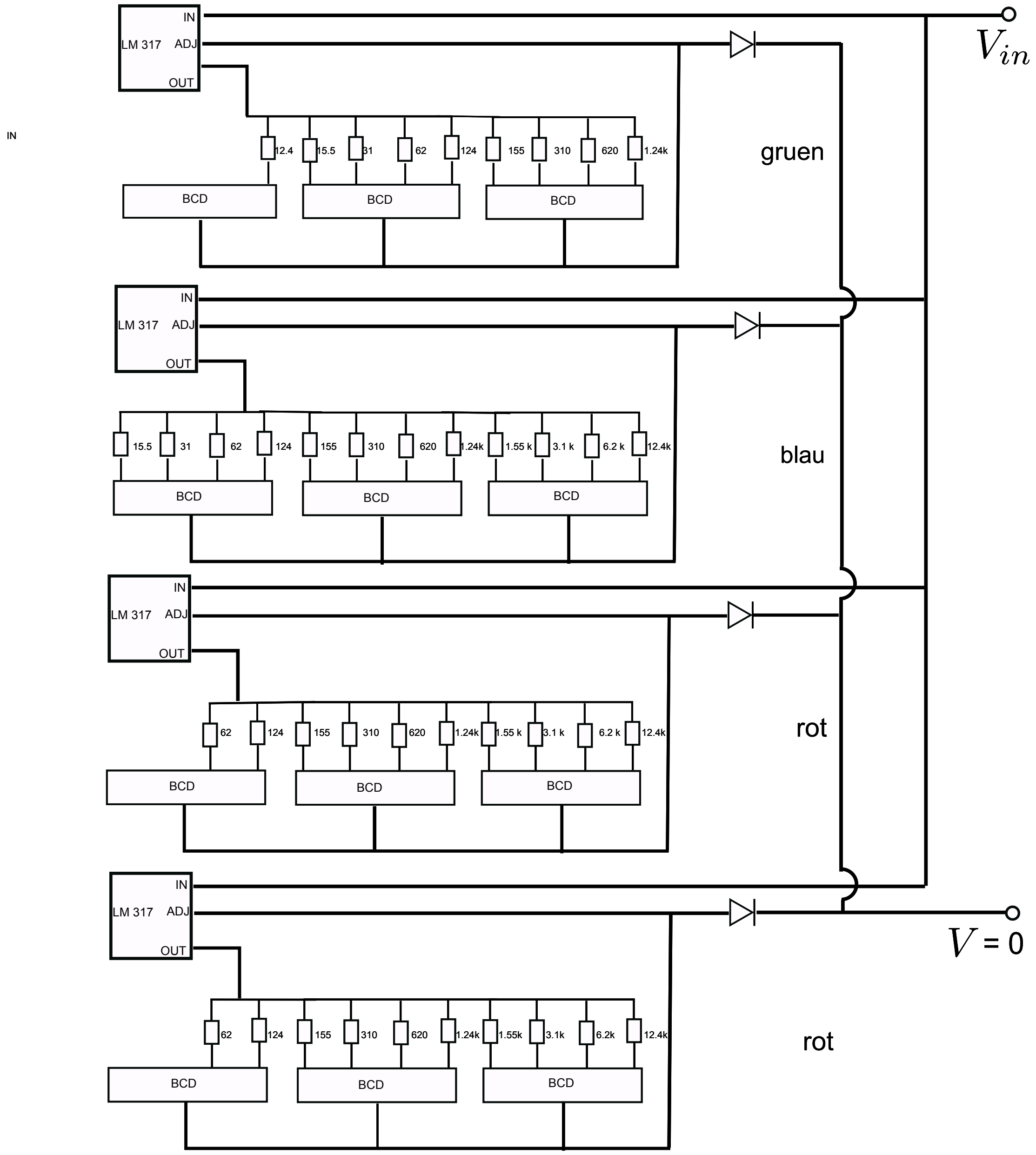


Figure 3.6: The laser diodes are powered by a current limiting power source.

So there is a special electrical power supply to operate the diodes (see figure 3.6 and 3.7). The foundation for this circuit can be seen in figure 3.5. The LM317 (see [Sem96]) is a voltage regulator that sees to it that between ADJ (adjust) and V_{OUT} is a constant voltage of 1.25 V. Changing the resistance R_1 also the current I_{OUT} changes with $I_{OUT} = \frac{1.25\text{ V}}{R_1}$. So this happens to be a adjustable current source. Instead of a potentiometer (like shown in figure 3.5) a combination of BCD switches (binary-coded-decimal switch) with the aid of which resistances are connected in series between V_{OUT} and ADJ is included here (see fig. 3.6).
The resistances are chosen in such a way that when for example for the green diode there is adjusted 1 in the right BCD switch and 0 in the two others, there is a current of 1 mA. We call this 001. When there is adjusted 1 in the BCD in the middle and 0 two others (010), there is a current of 10 mA. At the set-up 100 then yields a current of 100 mA. By this principle it is possible to adjust a current up to 999 mA but actually the resistances which would allow such a large current are left out, because the would damage the diodes. The part of the circuit that is responsible for the power supply of the green diode has resistances which allow a current up to 199 mA. The power supply for the blue diode can arrive 99.9 mA and the ones for the two red diodes 39.9 mA.

All the used resistances support a power of 0.25 W except at the smallest resistance of 12.4 Ω which supports a power of 5 W because there yields a current up to 100 mA. This circuit is driven with a voltage of 5 V. The current for the diodes is regulated adjusting the BCD switches.

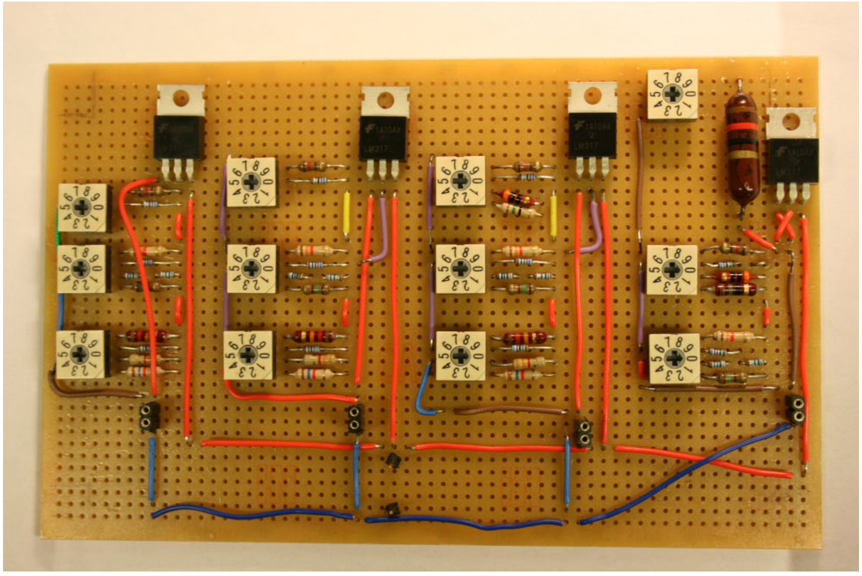


Figure 3.7: Picture of the constructed power source.

This type of gradually adjustable current source was designed by John Guy, an employee of "National Semiconductor" that is a producer of LM317 (see [Guy08]).
The circuit board will be included in a second level in the black box, where the optical components also are.

3.3 Complete set-up of the tunable light source

After finishing the construction of the main light source the set-up can be arranged. Light source, optical fibres, lenses, beam splitter and of course the blazed grating and the prism are part of the set-up. All components are mounted on an anodized plate (see appendix figure A.10), which has a metric grid of internal threads (see figure 3.8). Most of the mounted components are compatible with the measure of the grid. For some others it is necessary to construct adapters.
After installing the components on appropriate places on the plate, they have to be adjusted. The first aim is that the spectrum of the prism is right on top of the spectrum of the grating (see fig. 3.9). Then it is just necessary to change the height of the readout fibre, to switch between the two spectra.
Between the collimated light beam and the beam splitter there is added an iris diaphragm, which can be used to cut out the light.
The construction allows that the collimated light arrives the beam splitter cube at an incident angle of 0° in relation to the surface normal. The beam splitter divides the light into two beams which are guided to the prism and to the blazed grating, respectively. Like previously calculated (see [Ric10]) the rotating plates of the components are adjusted in a way that the beam of light arrives at the blazed grating at an angle of 30° to the surface normal and the prism at an angle of 70°. Therefore the arriving point of the light beam has to be on the rotation axis of the table.
Now the prism and the grating have to be positioned in a way that their spectra arrive at the readout fibre at the same point. In order to place the spectra one above the other one of the two dispersion components has to be inclined a bit which can be achieved by tilting one of the mounting posts.
The motor driver with the readout fibre is put to location where later on it will be possible to scan the whole projected spectrum over a range of 50 mm.

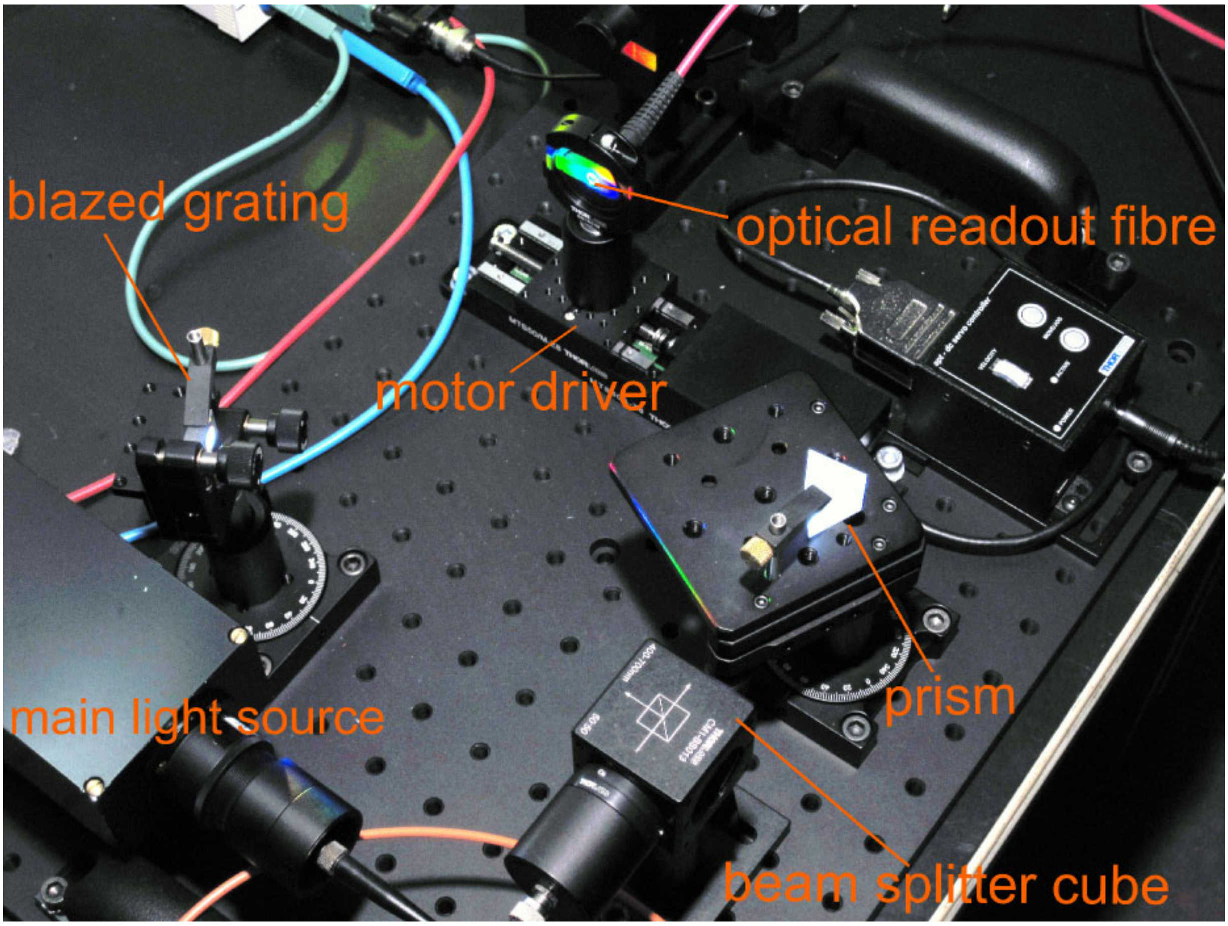


Figure 3.8: Complete set-up, all components are mounted on an anodized plate.

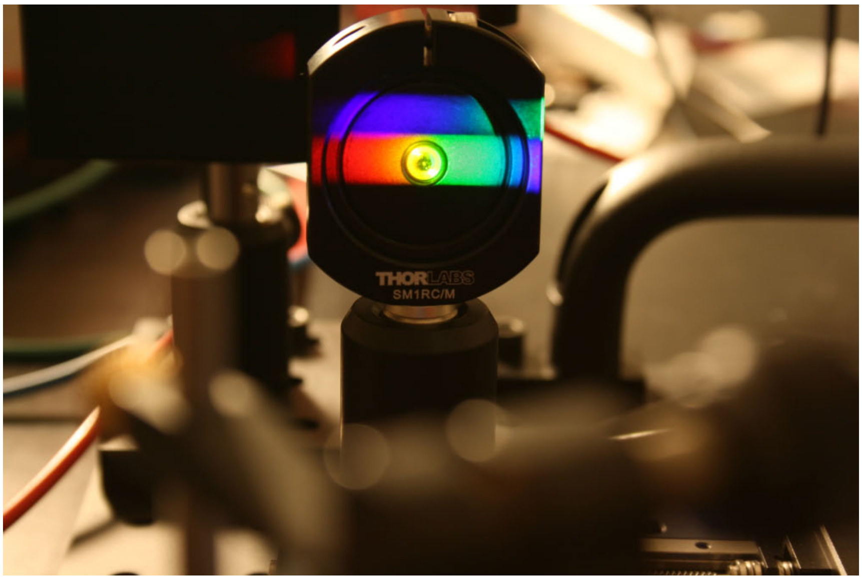
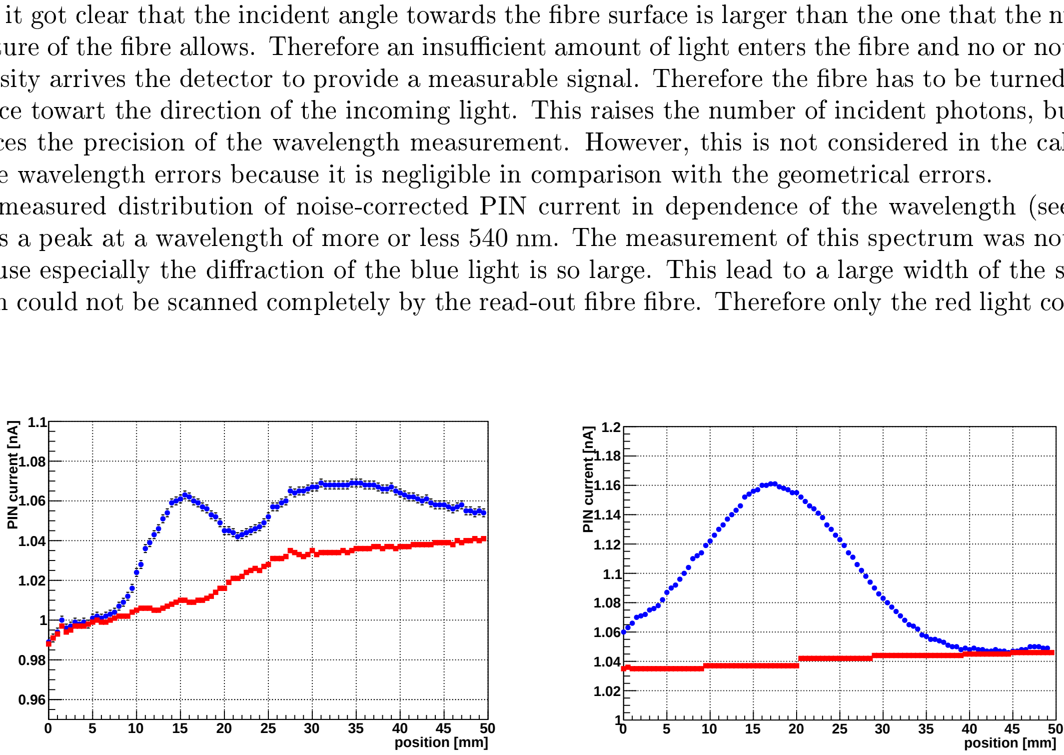


Figure 3.9: The spectra of grating and prism are both pointed to the readout fibre.

Chapter 4

First measurements and results

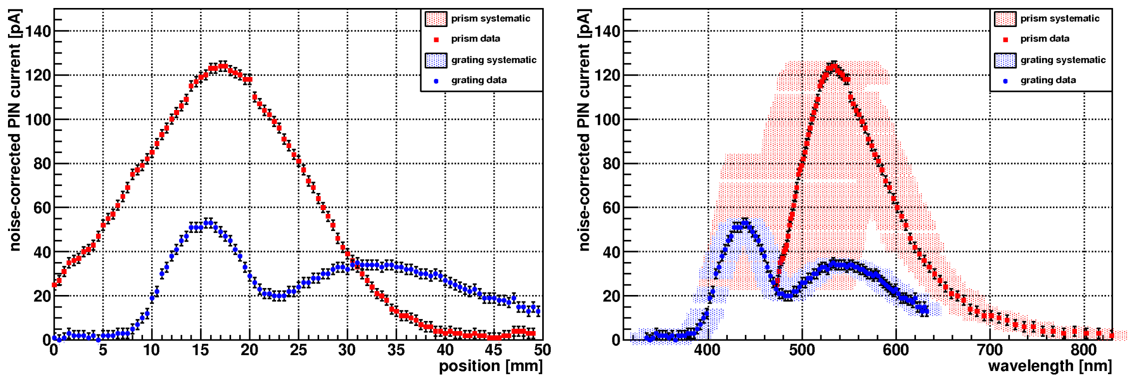
The aim of the first measurement with the currently existing set-up is to measure the photon flux density per mm^2 in dependence of the wavelength. This measurement is carried out with the PIN diode which is mounted on the integrating sphere.
First it is accomplished with the spectrum that comes from the blazed grating. The read-out fibre is adjusted to the height of the grating spectrum. Starting at the position of the blue spectral light the motor driver is used to move the fibre along the spectrum. Using the "move/jog" button, it is possible to make measurements in steps of 0.5 mm. The current of the PIN diode is measured with a picoammeter (see [Sch10b]). This measures the current with a resolution of 10 fA (see [Kei01]). About an hour before starting the measurement it has to be switched on so that it arrives at its operating temperature which usually influences the measurement. The PIN diode has a bias voltage of 10 V, it is reverse-biased. In the PIN diode there is a dark current which is also measured when no light arrives. Therefore for each measuring point two measurements are taken, one of the current of the incoming light and one of the dark current at this point. The dark current may still vary with time, so that its value has to be recorded at every point. There is also an internal offset of the picoammeter, but compared to the dark current it can be neglected. Afterwards the data are plotted with ROOT (see fig. 4.1(a)).
We perform the same measurements with the spectrum of the prism. In the prism the diffraction of the light is is inhomogeneous and particularly large for blue light (see section 2.1.5). In our first measurement of the spectrum of the prism it was not possible to achieve interpretable results. After some considerations it got clear that the incident angle towards the fibre surface is larger than the one that the numerical aperture of the fibre allows. Therefore an insufficient amount of light enters the fibre and no or not enough intensity arrives the detector to provide a measurable signal. Therefore the fibre has to be turned with its surface towart the direction of the incoming light. This raises the number of incident photons, but it also reduces the precision of the wavelength measurement. However, this is not considered in the calculation of the wavelength errors because it is negligible in comparison with the geometrical errors.
The measured distribution of noise-corrected PIN current in dependence of the wavelength (see 4.2(b)) shows a peak at a wavelength of more or less 540 nm. The measurement of this spectrum was not so easy because especially the diffraction of the blue light is so large. This lead to a large width of the spectrum which could not be scanned completely by the read-out fibre fibre. Therefore only the red light comes into view.



(a) Measurement of the grating's spectrum.

(b) Measurement of the prism's spectrum.

Figure 4.1: "Signal+noise" of the measurements of grating and prism.



(a) The noise-corrected PIN current is plotted against the position of the stage for prism and grating.

(b) The noise-corrected PIN current is plotted against the wavelength.

Figure 4.2: Plotting of the results.

To determine the real current which is driven by incoming photons, the measured noise is subtracted from the "signal + noise" value. A current of 1 A corresponds to $6.24 \cdot 10^{18} \frac{\text{electrons}}{\text{s}}$ $(\text{A} = \frac{\text{C}}{\text{s}})$. Measuring in picoampere $(= 10^{-12}\text{A})$ we have to know that 1 pA corresponds to $6.24 \cdot 10^{6} \frac{\text{electrons}}{\text{s}}$. Every measured electron was emitted after absorbing the energy of one photon. So at least the same number of photons as emitted electrons has arrived the PIN diode. Using the quantum efficiency of the used PIN diode (see fig. 2.17) it is possible to calculate the actual number of arriving photons (flux). Moreover the measurement provides results which are more applicable to the silicon photomultiplier, when the flux is given as flux per area (mm^2). Therefore it is necessary to divide the values by the active area of the PIN diode (25mm^2). The results of these measurements and calculations are shown in fig. 4.3.

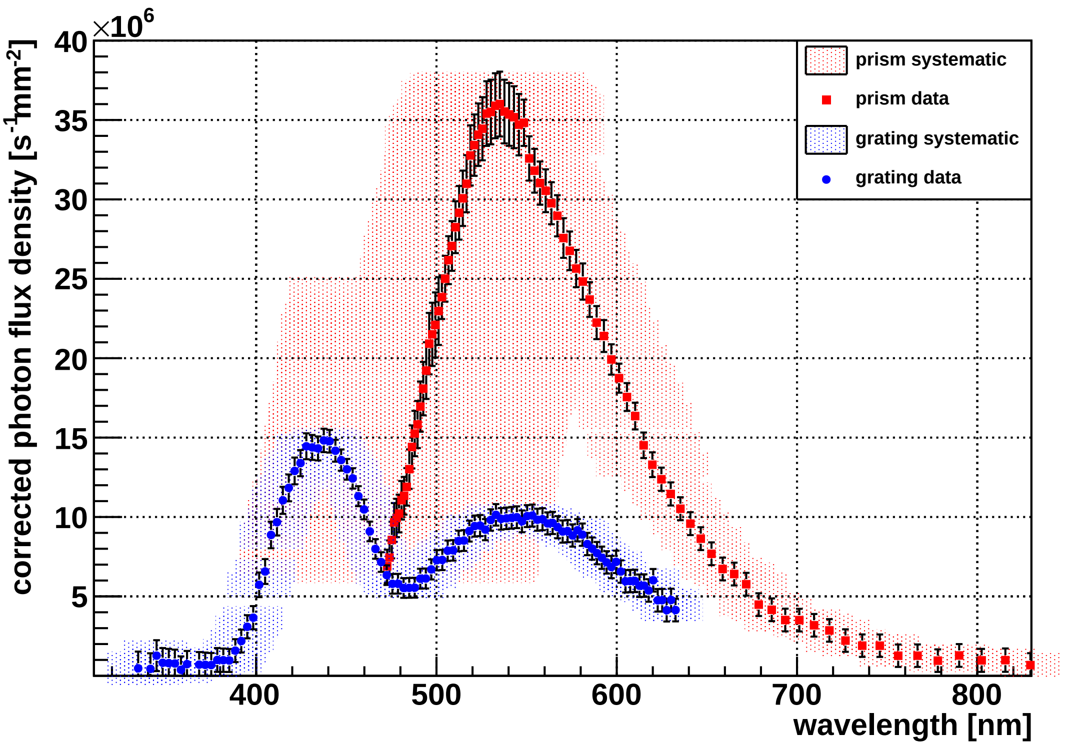


Figure 4.3: The photon flux density is the aim of the first measurement with the current finished set-up.

For this plot it was also necessary to convert the positions in mm in the corresponding wavelengths. For this calculation see [Ric10]. For example at a wavelength of approximately 540 nm (for the grating) there is a photon flux density of $10^7 \frac{\text{photons}}{\text{s} \quad \text{mm}^2}$. The area of one pixel of an SiPM is $100{\times}100\ \mu\text{m}^2 = 10^{-2}\text{mm}^2$ and arriving pulses are not longer than 100 ns. That means there arrive approximately 10^{-2} photons in 100 ns

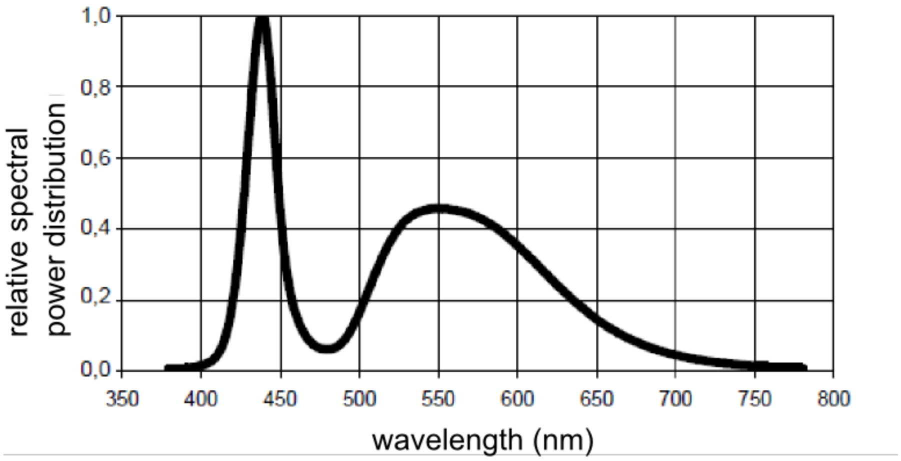


Figure 4.4: Spectrum of a typical white diode [Lux04].

per $100 \times 100\mu\text{m}^2$. For this interval the photon flux is quite small and the SiPM could be operated under this conditions. In order to measure real photon detection efficiencies the light has to be pulsed and the intensity has to be increased, to guarantee a sufficient amount of arriving photons.
The error bars regarding the wavelengths result from geometrical uncertainty positioning the grating and the prism which propagates into the wavelengths errors. For calculation of the errors in the measurement with the prism different quantities are important than for the calculations of the grating errors. The wavelength errors of the prism are larger than of the grating [Ric10]. The error of the current is estimated considering the exactness of the picoammeter, because values vary by 1 pA to 2 pA. It is estimated as 1 pA for the measurement of the underground and as 2 pA for the values.

Comparing these data with the expected spectrum (see fig. 4.4) of the used white diode, we can see that the measurement provides good results which qualitatively represent the expected characteristics. Otherwise it also stands out that in the used white LED the percentage of blue light is lower than in the spectrum of the typical LED. There (fig. 4.4) the proportion of the blue light is clearly larger than the one of the rest of the wavelengths. This shows us the differentiation between warm and cold light. In a warm light LED the intensities of the different wavelengths are more even distributed. Cold light has a larger percentage of blue light. The used LED emits neither warm nor cold light but it is evident that it is different from the spectrum of the typical white LED.

Comparing the two measured photon fluxes which are measured with the two different spectra it is evident that the photon flux of the prism's spectrum is larger than the one of the grating. This may be connected with the turning of the fibre to optimise the measurement of the prism's spectrum. This could have enabled a better transmission of the light into the fibre.

All in all it can be said that the spectral analysis is much more convenient with the grating's spectrum. The adjusting is more precise with the grating and therefore the errors are smaller than with the prism. Especially the blue light of the prism's spectrum arrives at the read-out fibre in a very large incident angle, which complicates the measurements. The grating's spectrum arrives at the fibre's surface in more acute angles relative to the surface normal.

Chapter 5

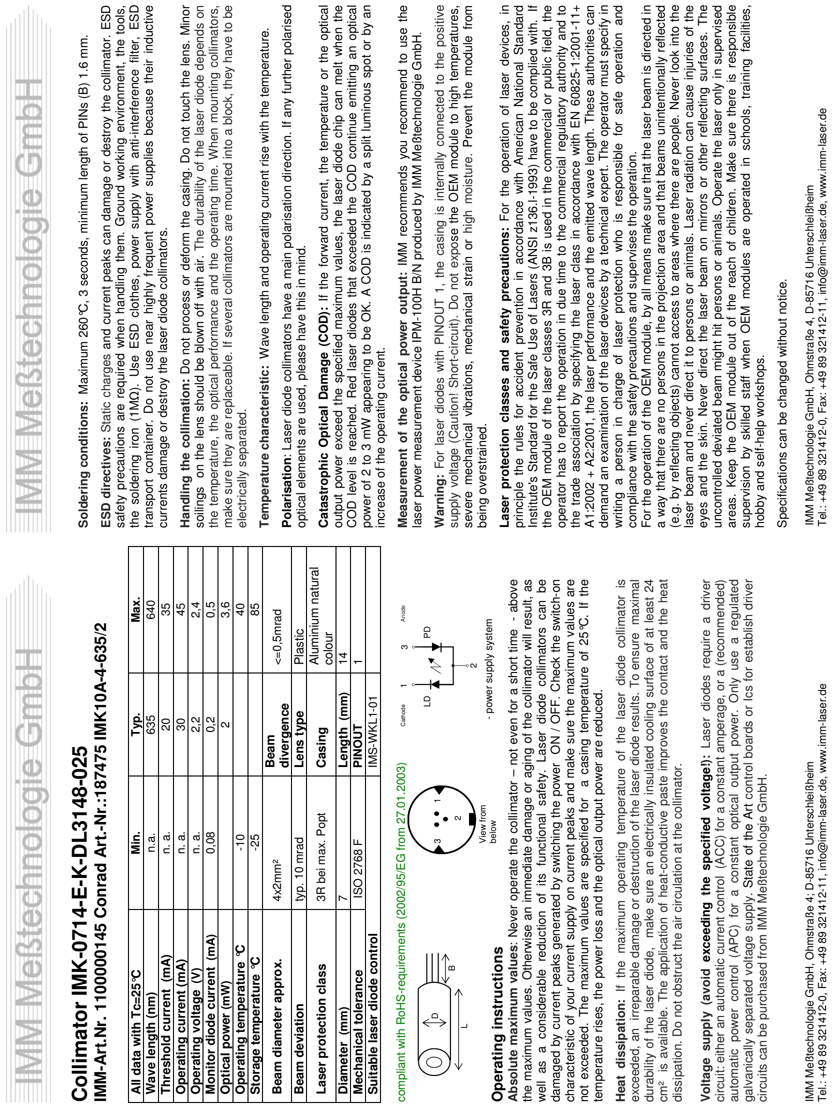
Conclusions and Outlook

The constructed tunable light source shall serve as test stand for measurements of the photo detection efficiency of silicon photomultipliers. In this project it was achieved to assemble all necessary components in the set-up and to make first measurements using a PIN diode as reference detector. The first task was to couple as much as possible light from the light source into the fibre. This was achieved by optimising a condenser to focus the light into the fibre. After leaving the fibre the light was collimated by an aspheric lens. Calculations were performed to adjust the prism and the blazed grating to get the suitable incidence angle. Afterwards the spectral light could be scanned step by step with the motorised stage and coupled into the integrating sphere by an optical fibre. The first measurements of the photon flux density with the PIN diode as detector provided the expected results. Moreover it shows that the measurements are more convenient using the blazed grating for spectral colour dispersion.
The only exception which could not be constructed before finishing the project is the reference light source for the calibration.

Further additions and changes are required for fully functional test stand: Using the light source for the testing of silicon photomultipliers demands a pulsed light source because a silicon photomultiplier is not suitable for high photon fluxes so that it could be exposed to a permanently emitting light source.
Moreover there are some possibilities to adjust the set-up better than now. The first step could be to install a white LED with higher power to get more intensive light. By this it could be possible to do the readout with a smaller fibre to raise the precision of the wavelength measurement. Besides a more intensive LED the intensity of the light can also be enhanced by another condenser which is optimised for the used light source.
The reference light source is important for a more precise calibration of the positions of the wavelengths. There will be four reference points in the spectrum with which the positions can be calibrated. So the finishing of the reference light source is significant task to be accomplished.
After knowing exactly the position of each spectral wavelength the last step will be to program the motor driver and the picoammeter in order to have automated adjustment and readout.

Appendix A

Datasheets of the Components



IMM Meßtechnologie GmbH

Collimator IMK-0714-E-K-DL3148-025
IMM-Art.Nr. 1100000145 Conrad Art.-Nr.:187475 IMK10A-4-635/2

All data with Tc=25℃	Min.	Typ.	Max.
Wave length (nm)	n.a.	635	640
Threshold current (mA)	n. a.	20	35
Operating current (mA)	n. a.	30	45
Operating voltage (V)	n. a.	2,2	2,4
Monitor diode current (mA)	0,08	0,2	0,5
Optical power (mW)		2	3,6
Operating temperature ℃	-10		40
Storage temperature ℃	-25		85
Beam diameter approx.	4x2mm²	Beam divergence	<=0,5mrad
Beam deviation	typ. 10 mrad	Lens type	Plastic
Laser protection class	3R bei max. Popt	Casing	Aluminium natural colour
Diameter (mm)	7	Length (mm)	14
Mechanical tolerance	ISO 2768 F	PINOUT	1
Suitable laser diode control		IMS-WKL1-01	

compliant with RoHS-requirements (2002/95/EG from 27.01.2003)

Operating instructions

Absolute maximum values: Never operate the collimator – not even for a short time - above the maximum values. Otherwise an immediate damage or aging of the collimator will result, as well as a considerable reduction of its functional safety. Laser diode collimators can be damaged by current peaks generated by switching the power ON / OFF. Check the switch-on characteristic of your current supply on current peaks and make sure the maximum values are not exceeded. The maximum values are specified for a casing temperature of 25℃. If the temperature rises, the power loss and the optical output power are reduced.

Heat dissipation: If the maximum operating temperature of the laser diode collimator is exceeded, an irreparable damage or destruction of the laser diode results. To ensure maximal durability of the laser diode, make sure an electrically insulated cooling surface of at least 24 cm² is available. The application of heat-conductive paste improves the contact and the heat dissipation. Do not obstruct the air circulation at the collimator.

Voltage supply (avoid exceeding the specified voltage!): Laser diodes require a driver circuit: either an automatic current control (ACC) for a constant amperage, or a (recommended) automatic power control (APC) for a constant optical output power. Only use a regulated galvanically separated voltage supply. State of the Art control boards or Ics for establish driver circuits can be purchased from IMM Meßtechnologie GmbH.

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Tel.: +49 89 321412-0, Fax: +49 89 321412-11, info@imm-laser.de, www.imm-laser.de

IMM Meßtechnologie GmbH

Soldering conditions: Maximum 260℃, 3 seconds, minimum length of PINs (B) 1.6 mm.

ESD directives: Static charges and current peaks can damage or destroy the collimator. ESD safety precautions are required when handling them. Ground working environment, the tools, the soldering iron (1MΩ). Use ESD clothes, power supply with anti-interference filter, ESD transport container. Do not use near highly frequent power supplies because their inductive currents damage or destroy the laser diode collimators.

Handling the collimation: Do not process or deform the casing. Do not touch the lens. Minor soilings on the lens should be blown off with air. The durability of the laser diode depends on the temperature, the optical performance and the operating time. When mounting collimators, make sure they are replaceable. If several collimators are mounted into a block, they have to be electrically separated.

Temperature characteristic: Wave length and operating current rise with the temperature.

Polarisation: Laser diode collimators have a main polarisation direction. If any further polarised optical elements are used, please have this in mind.

Catastrophic Optical Damage (COD): If the forward current, the temperature or the optical output power exceed the specified maximum values, the laser diode chip can melt when the COD level is reached. Red laser diodes that exceeded the COD continue emitting an optical power of 2 to 3 mW appearing to be OK. A COD is indicated by a split luminous spot or by an increase of the operating current.

Measurement of the optical power output: IMM recommends you recommend to use the laser power measurement device IPM-100H B/N produced by IMM Meßtechnologie GmbH.

Warning: For laser diodes with PINOUT 1, the casing is internally connected to the positive supply voltage (Caution! Short-circuit). Do not expose the OEM module to high temperatures, severe mechanical vibrations, mechanical strain or high moisture. Prevent the module from being overstrained.

Laser protection classes and safety precautions: For the operation of laser devices, in principle the rules for accident prevention in accordance with American National Standard Institute's Standard for the Safe Use of Lasers (ANSI z136.l-1993) have to be complied with. If the OEM module of the laser classes 3R and 3B is used in the commercial or public field, the operator has to report the operation in due time to the commercial regulatory authority and to the trade association by specifying the laser class in accordance with EN 60825-1:2001-11+ A1:2002 + A2:2001, the laser performance and the emitted wave length. These authorities can demand an examination of the laser devices by a technical expert. The operator must specify in writing a person in charge of laser protection who is responsible for safe operation and compliance with the safety precautions and supervises the operation.
For the operation of the OEM module, by all means make sure that the laser beam is directed in a way that there are no persons in the projection area and that beams unintentionally reflected (e.g. by reflecting objects) cannot access to areas where there are people. Never look into the laser beam and never direct it to persons or animals. Laser radiation can cause injuries of the eyes and the skin. Never direct the laser beam on mirrors or other reflecting surfaces. The uncontrolled deviated beam might hit persons or animals. Operate the laser only in supervised areas. Keep the OEM module out of the reach of children. Make sure there is responsible supervision by skilled staff when OEM modules are operated in schools, training facilities, hobby and self-help workshops.

Specifications can be changed without notice.

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Figure A.1: Datasheet of the red laser diode with $\lambda = 635$ nm.

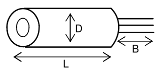
IMM Meßtechnologie GmbH

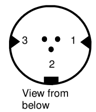
Collimator IMK-0714-E-K-DL3149-057

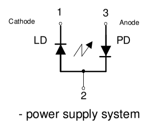
IMM-Art.Nr. 1100000316 Conrad Art.-Nr.:187514 IMK10A-4-670/3,5

All data with Tc=25℃	Min.	Typ.	Max.
Wave length (nm)	660.	670	678
Threshold current (mA)	n. a.	25	35
Operating current (mA)	n. a.	40	45
Operating voltage (V)	n. a.	2,3	2,6
Monitor diode current (mA)	0,5	1,5	2
Optical power (mW)		3,5	4,2
Operating temperature ℃	-10		60
Storage temperature ℃	-25		85
Beam diameter approx.	4x2mm²	Beam divergence	<=0,5mrad
Beam deviation	typ. 10 mrad	Lens type	Plastic
Laser protection class	3R bei max. Popt	Casing	Aluminium natural colour
Diameter (mm)	7	Length (mm)	14
Mechanical tolerance	ISO 2768 F	PINOUT	1
Suitable laser diode control		IMS-WKL1-01	

compliant with RoHS-requirements (2002/95/EG from 27.01.2003)







Operating instructions

Absolute maximum values: Never operate the collimator – not even for a short time - above the maximum values. Otherwise an immediate damage or aging of the collimator will result, as well as a considerable reduction of its functional safety. Laser diode collimators can be damaged by current peaks generated by switching the power ON / OFF. Check the switch-on characteristic of your current supply on current peaks and make sure the maximum values are not exceeded. The maximum values are specified for a casing temperature of 25℃. If the temperature rises, the power loss and the optical output power are reduced.

Heat dissipation: If the maximum operating temperature of the laser diode collimator is exceeded, an irreparable damage or destruction of the laser diode results. To ensure maximal durability of the laser diode, make sure an electrically insulated cooling surface of at least 24 cm² is available. The application of heat-conductive paste improves the contact and the heat dissipation. Do not obstruct the air circulation at the collimator.

Voltage supply (avoid exceeding the specified voltage!): Laser diodes require a driver circuit: either an automatic current control (ACC) for a constant amperage, or a (recommended) automatic power control (APC) for a constant optical output power. Only use a regulated galvanically separated voltage supply. State of the Art control boards or Ics for establish driver circuits can be purchased from IMM Meßtechnologie GmbH.

IMM Meßtechnologie GmbH, Ohmstraße 4; D-85716 Unterschleißheim
Tel.: +49 89 321412-0, Fax: +49 89 321412-11, info@imm-laser.de, www.imm-laser.de

IMM Meßtechnologie GmbH

Soldering conditions: Maximum 260℃, 3 seconds, minimum length of PINs (B) 1.6 mm.

ESD directives: Static charges and current peaks can damage or destroy the collimator. ESD safety precautions are required when handling them. Ground working environment, the tools, the soldering iron (1MΩ). Use ESD clothes, power supply with anti-interference filter, ESD transport container. Do not use near highly frequent power supplies because their inductive currents damage or destroy the laser diode collimators.

Handling the collimation: Do not process or deform the casing. Do not touch the lens. Minor soilings on the lens should be blown off with air. The durability of the laser diode depends on the temperature, the optical performance and the operating time. When mounting collimators, make sure they are replaceable. If several collimators are mounted into a block, they have to be electrically separated.

Temperature characteristic: Wave length and operating current rise with the temperature.

Polarisation: Laser diode collimators have a main polarisation direction. If any further polarised optical elements are used, please have this in mind.

Catastrophic Optical Damage (COD): If the forward current, the temperature or the optical output power exceed the specified maximum values, the laser diode chip can melt when the COD level is reached. Red laser diodes that exceeded the COD continue emitting an optical power of 2 to 3 mW appearing to be OK. A COD is indicated by a split luminous spot or by an increase of the operating current.

Measurement of the optical power output: IMM recommends you recommend to use the laser power measurement device IPM-100H B/N produced by IMM Meßtechnologie GmbH.

Warning: For laser diodes with PINOUT 1, the casing is internally connected to the positive supply voltage (Caution! Short-circuit). Do not expose the OEM module to high temperatures, severe mechanical vibrations, mechanical strain or high moisture. Prevent the module from being overstrained.

Laser protection classes and safety precautions: For the operation of laser devices, in principle the rules for accident prevention in accordance with American National Standard Institute's Standard for the Safe Use of Lasers (ANSI z136.I-1993) have to be complied with. If the OEM module of the laser classes 3R and 3B is used in the commercial or public field, the operator has to report the operation in due time to the commercial regulatory authority and to the trade association by specifying the laser class in accordance with EN 60825-1:2001-11+ A1:2002 + A2:2001, the laser performance and the emitted wave length. These authorities can demand an examination of the laser devices by a technical expert. The operator must specify in writing a person in charge of laser protection who is responsible for safe operation and compliance with the safety precautions and supervises the operation.
For the operation of the OEM module, by all means make sure that the laser beam is directed in a way that there are no persons in the projection area and that beams unintentionally reflected (e.g. by reflecting objects) cannot access to areas where there are people. Never look into the laser beam and never direct it to persons or animals. Laser radiation can cause injuries of the eyes and the skin. Never direct the laser beam on mirrors or other reflecting surfaces. The uncontrolled deviated beam might hit persons or animals. Operate the laser only in supervised areas. Keep the OEM module out of the reach of children. Make sure there is responsible supervision by skilled staff when OEM modules are operated in schools, training facilities, hobby and self-help workshops.

Specifications can be changed without notice.

IMM Meßtechnologie GmbH, Ohmstraße 4, D-85716 Unterschleißheim
Tel.: +49 89 321412-0, Fax: +49 89 321412-11, info@imm-laser.de, www.imm-laser.de

Figure A.2: Datasheet of the red laser diode with $\lambda = 670$ nm.

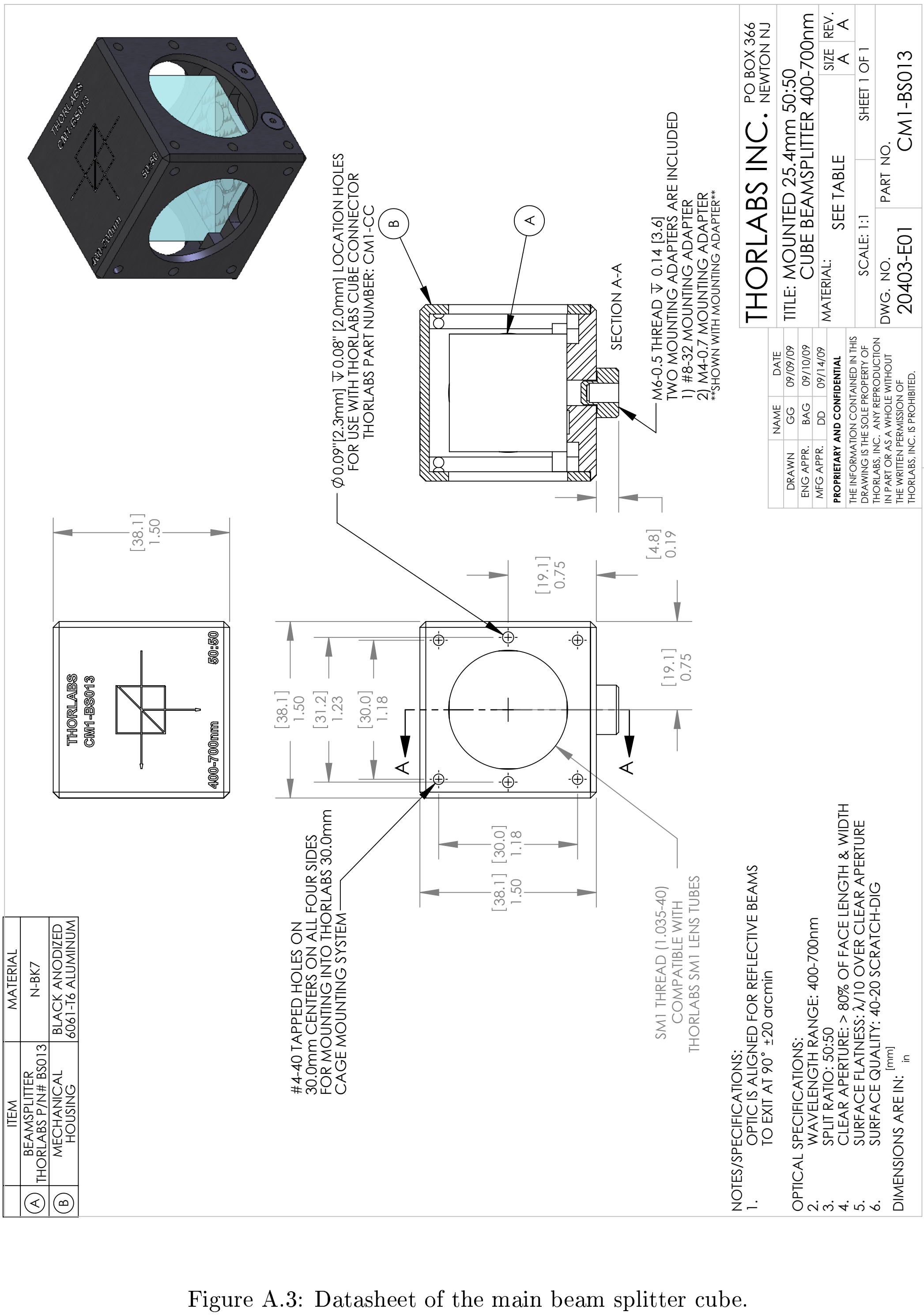
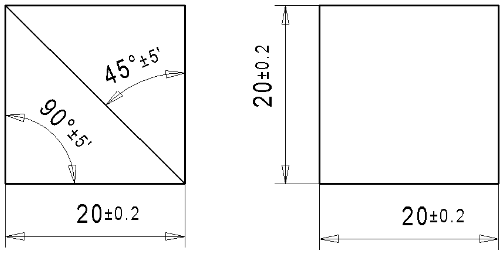


Figure A.3: Datasheet of the main beam splitter cube.

DATA SHEET	**CUBE BEAMSPLITTER**

Description: Separates a beam of light into two separate beams.

ID	**2105**
Reflection/Transmission	50/50 @550nm
Dimensional Tolerances	±0.2mm
Angle Tolerances	±5arcmin
Surface Quality (Scratch/Dig)	60-40
Surface accuracy	1/2 Lambda
Bevel	0.3mm x 45°



Optical Glass H-K9L
Corresponding glass types:
BSC7, N-BK7, S-BSL7
ROHS: Compliant

n_d=1.51680	ν_d=64.20
n_e=1.51872	ν_e=64.0

Thermal Properties	
T_g (°C)	565
T_s (°C)	630
$T_{10^{14.5}}$ (°C)	511
$T_{10^{13}}$ (°C)	547
α (-60...20 °C (10^{-7}/K)	75
α (20...300 °C) (10^{-7}/K)	82

Mechanical Properties	
H_K (10^7Pa)	595
F_A	1.00
E (10^7Pa)	7920
G (10^7Pa)	3270
μ	0.211

Stress-Optical Coefficient	
B (10^{-12}/Pa)	2.70

Coloration Code	
λ_{80}/λ_5	33/29

Other Properties	
ρ (g/cm³)	2.52

Refractive Indices		
	[λ]=nm	
n_r	706.5	1.5128
n_c	656.3	1.51432
$n_{c'}$	643.8	1.51472
$n_{He\text{-}Ne}$	632.8	1.51509
n_D	589.3	1.51673
n_d	587.6	1.51680
n_e	546.1	1.51872
n_F	486.1	1.52237
$n_{F'}$	480.0	1.52282
n_g	435.8	1.52667
n_h	404.7	1.53022
n_i	365.0	1.53622

Constants of Dispersion Formula	
A_0	2.2702566
A_1	$-9.1988101 \cdot 10^{-3}$
A_1	$1.1609706 \cdot 10^{-2}$
A_3	$-7.6123911 \cdot 10^{-5}$
A_4	$2.8558727 \cdot 10^{-5}$
A_5	$-1.2566486 \cdot 10^{-6}$

Relative Partial Dispersions			
$P_{d,c}$	0.3080	$P'_{d,c}$	0.2569
$P_{e,d}$	0.2387	$P'_{e,d}$	0.2371
$P_{g,F}$	0.5342	$P'_{g,F}$	0.4748

Deviation of relative Partial Dispersions ΔP from the Normal Line	
$\Delta P_{F,e}$	-0.0014
$\Delta P_{g,F}$	-0.0035

Internal Transmittance		
λ (nm)	at 5mm	at 10mm
2400	0.86	0.74
2200	0.930	0.86
2000	0.960	0.922
1800	0.985	0.970
1600	0.990	0.980
1400	0.995	0.990
1200	0.998	0.996
1060	0.998	0.996
1000	0.999	0.997
950	0.999	0.997
900	0.999	0.998
850	0.999	0.998
800	0.999	0.999
700	0.999	0.999
650	0.999	0.998
600	0.999	0.999
550	0.999	0.999
500	0.999	0.998
480	0.999	0.998
460	0.999	0.998
440	0.999	0.997
420	0.999	0.998
400	0.999	0.998
390	0.998	0.997
380	0.997	0.993
370	0.997	0.993
360	0.994	0.988
350	0.989	0.977
340	0.977	0.954
330	0.95	0.91
320	0.90	0.8
310	0.80	0.63
300	0.61	0.38
290	0.36	0.13
280	0.14	0.02

GERÄTETECHNIK Dipl.-Ing. Ulf Mikolajczak, Trakehnenstr. 6a, 26127 Oldenburg, Germany
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Figure A.4: Datasheet of the smaller cubes for the reference light source [Mik10].

Data Sheet

SCHOTT

N-SF11
785257.322

n_d = 1.78472	ν_d = 25.68	$n_F - n_C$ = 0.030558
n_e = 1.79192	ν_e = 25.47	$n_{F'} - n_{C'}$ = 0.031088

Refractive Indices

	λ [nm]	
$n_{2325.4}$	2325.4	1.72937
$n_{1970.1}$	1970.1	1.73600
$n_{1529.6}$	1529.6	1.74377
$n_{1060.0}$	1060.0	1.75401
n_t	1014.0	1.75542
n_s	852.1	1.76182
n_r	706.5	1.77119
n_C	656.3	1.77596
$n_{C'}$	643.8	1.77732
$n_{632.8}$	632.8	1.77860
n_D	589.3	1.78446
n_d	587.6	1.78472
n_e	546.1	1.79192
n_F	486.1	1.80651
$n_{F'}$	480.0	1.80841
n_g	435.8	1.82533
n_h	404.7	1.84235
n_i	365.0	
$n_{334.1}$	334.1	
$n_{312.6}$	312.6	
$n_{296.7}$	296.7	
$n_{280.4}$	280.4	
$n_{248.3}$	248.3	

Constants of Dispersion Formula

B_1	1.73759695
B_2	0.313747346
B_3	1.89878101
C_1	0.013188707
C_2	0.0623068142
C_3	155.23629

Constants of Dispersion dn/dT

D_0	$-3.56 \cdot 10^{-6}$
D_1	$9.20 \cdot 10^{-9}$
D_2	$-2.10 \cdot 10^{-11}$
E_0	$9.65 \cdot 10^{-7}$
E_1	$1.44 \cdot 10^{-9}$
λ_{TK} [μm]	0.294

Internal Transmittance τ_i

λ [nm]	τ_i (10mm)	τ_i (25mm)
2500	0.826	0.620
2325	0.867	0.700
1970	0.965	0.915
1530	0.994	0.985
1060	0.999	0.998
700	0.994	0.985
660	0.992	0.981
620	0.992	0.981
580	0.994	0.984
546	0.991	0.978
500	0.981	0.953
460	0.967	0.920
436	0.946	0.870
420	0.919	0.810
405	0.852	0.670
400	0.815	0.600
390	0.686	0.390
380	0.428	0.120
370	0.083	0.002
365		
350		
334		
320		
310		
300		
290		
280		
270		
260		
250		

Color Code

λ_{80}/λ_5	44/37
(*= λ_{70}/λ_5)	

Remarks

Relative Partial Dispersion

$P_{s,t}$	0.2095
$P_{C,s}$	0.4625
$P_{d,C}$	0.2868
$P_{e,d}$	0.2355
$P_{g,F}$	0.6156
$P_{i,h}$	
$P'_{s,t}$	0.2059
$P'_{C',s}$	0.4984
$P'_{d,C'}$	0.2381
$P'_{e,d}$	0.2315
$P'_{g,F'}$	0.5442
$P'_{i,h}$	

Deviation of Relative Partial Dispersions ΔP from the "Normal Line"

$\Delta P_{C,t}$	0.0052
$\Delta P_{C,s}$	-0.0003
$\Delta P_{F,e}$	0.0027
$\Delta P_{g,F}$	0.0150
$\Delta P_{i,g}$	

Other Properties

$\alpha_{-30/+70°C}$ [10^{-6}/K]	8.5
$\alpha_{+20/+300°C}$ [10^{-6}/K]	9.9
T_g [°C]	592
$T_{10}^{13.0}$ [°C]	590
$T_{10}^{7.6}$ [°C]	688
c_p [J/(g·K)]	0.710
λ [W/(m·K)]	0.950
ρ [g/cm^3]	3.22
E [10^3 N/mm^2]	92
μ	0.257
K [10^{-6} mm^2/N]	2.94
$HK_{0.1/20}$	615
HG	4
B	1
CR	1
FR	0
SR	1
AR	1
PR	1

Temperature Coefficients of Refractive Index

	$\Delta n_{rel}/\Delta T$ [10^{-6}/K]			$\Delta n_{abs}/\Delta T$ [10^{-6}/K]		
[°C]	1060.0	e	g	1060.0	e	g
-40/ -20	0.1	2.0	4.6	-2.3	-0.5	2.1
+20/ +40	0.1	2.4	5.6	-1.4	0.8	4.0
+60/ +80	0.2	2.7	6.3	-1.0	1.5	5.1

As of /05/12/2006, Subject to change

79 | Overview

Figure A.5: The used prism consists of N-SF11 glass [Sch10a].

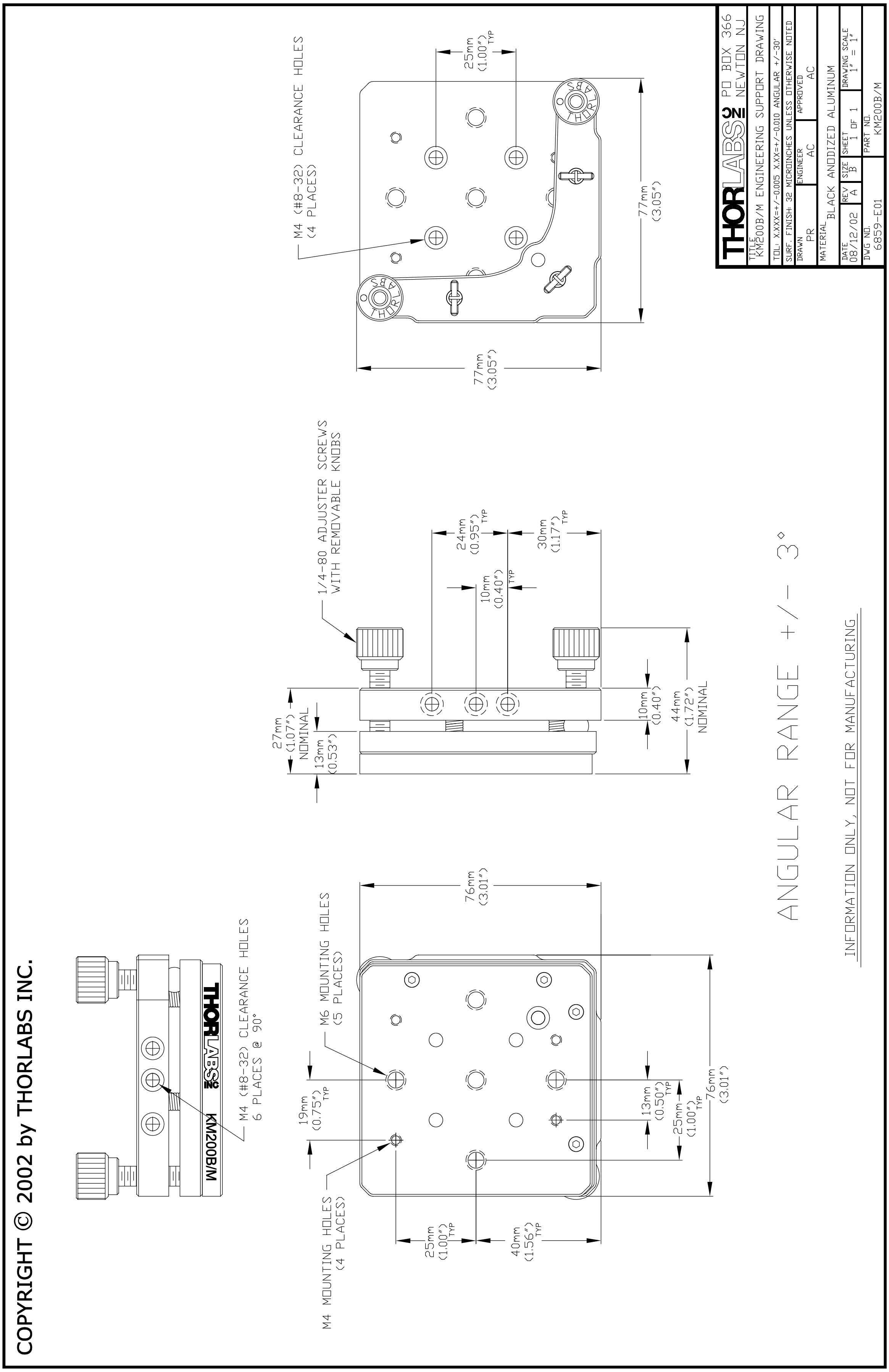


Figure A.6: Drawing of the plate on which the prism is mounted [Tho10c].

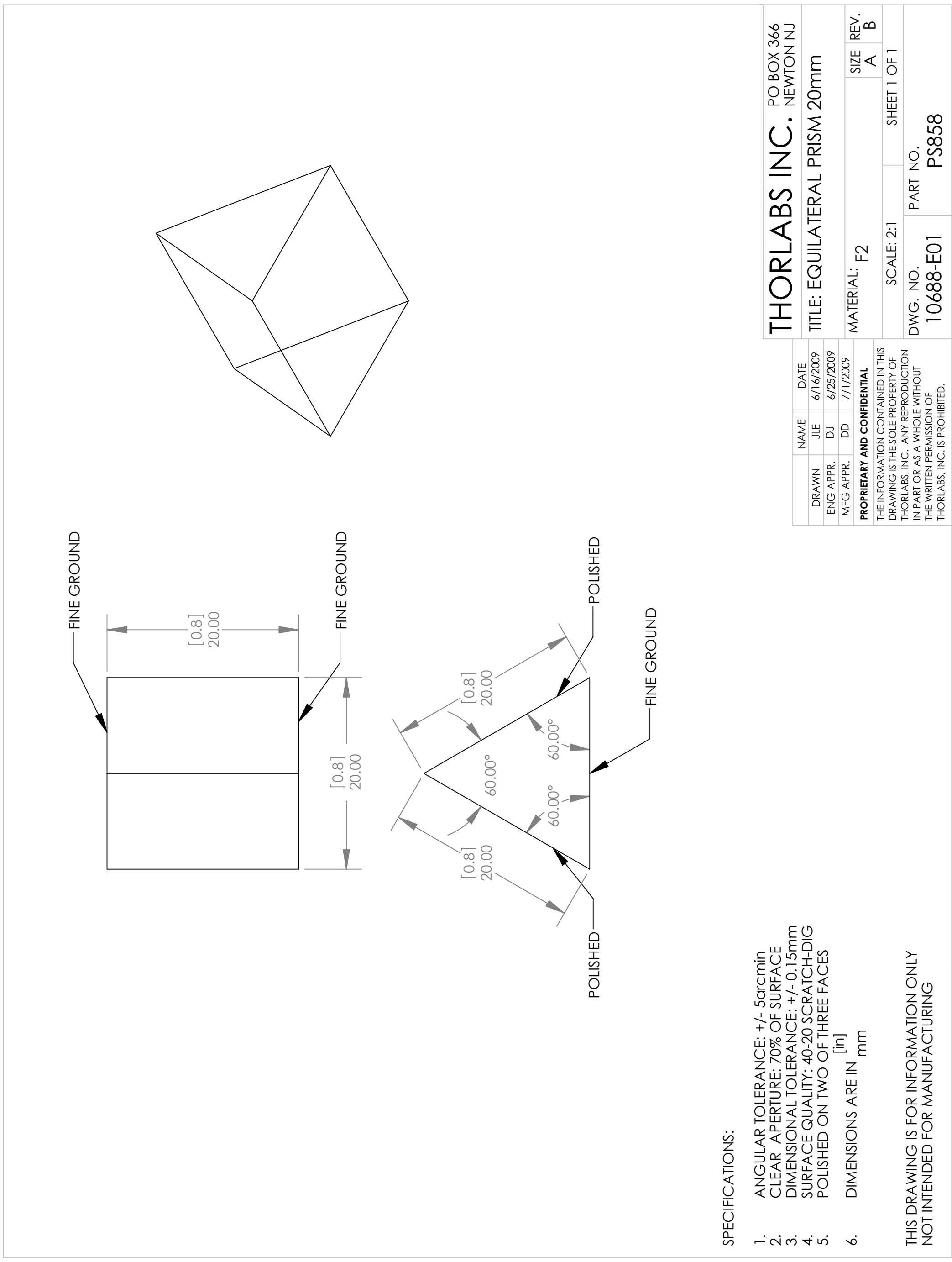


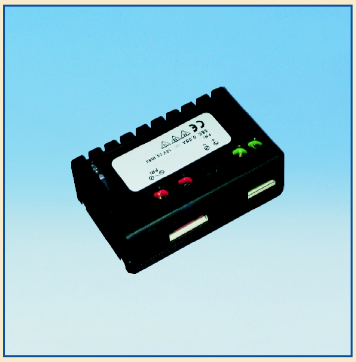
Figure A.7: Catalogue page of the used prism [Tho10c].

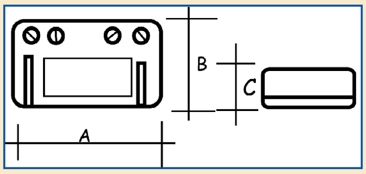
Datenblatt - Datasheet

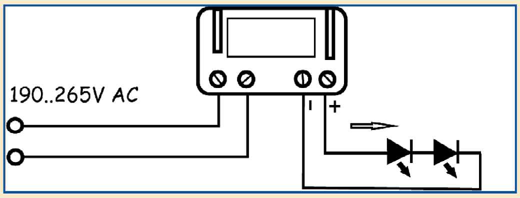
Barthelme

Power LED Konverter für Netzspannung / Power LED converter for main voltage

CE EMC SELV







		LEDTREIB10	LEDTREIB32
		MPL 1	MPL 4
Eingangsspannung/Input voltage	(V)	195-265V / AC	195-265V / AC
Frequenz / Frequency	(Hz)	50-60	50-60
Ausgangsstrom/Output current	(mA)	350	700
LEDs min		1	1
LEDs max		2*	1
Schutzart/Protection		IP 20	IP 20
Isolationsklasse/Insulation class		I I	I I
Umgebungstemperatur/Ambient temperature	(°C)	40-65	40-65
Gewicht / Weight	(g)	25	25
Abmessungen / Dimensions	(mm)	51x32x18 mm	51x32x18 mm

bei Verwendung von roten Power LEDs max. 1 LED / *when driving red Power LEDs use max .1 LED

LED Konverter - Installationsanweisungen

Die Konstantstrom Konverter dürfen ausschließlich in Verbindung mit Power LEDs (High Brightness LEDs) eingesetzt werden. Achten Sie darauf, dass die entsprechenden LEDs auch für den Ausgangsstrom des Konverters ausgelegt sind. Die LEDs immer in Reihe anschließen! Die maximal anzuschließende Anzahl der LEDs ist abhängig vom verwendeten Typ. Die Polarität des Ausgangs beachten. Den Konverter nicht in der Nähe von Wärmequellen und nur an gut belüfteten Orten einsetzten. Thermischer Schutz: Falls die Temperatur zu hoch wird, schaltet sich der Konverter ab und schaltet sich wieder ein wenn der Konverter sich abgekühlt ist. LEDs nur im ausgeschalteten Zustand anschließen. Kurzschlüsse auf der Sekundärseite vermeiden. Klemmschrauben vorsichtig anziehen. Als Anschlussleitung 0,5mm² bis 1,5mm² und eine maximale Länge von 10m verwenden.
Eingangsverkabelung: H03VVH2F 2x0,75mm² Kabel verwenden.

LED Drivers - Installation instructions

The drivers are working with constant current and must only be used with Power LEDs (High Brightness LEDs) which have the same current consumption as indicated on the driver. The max. number of LEDs that can be connected to the driver depends on the kind of used LEDs. Connect the LEDs always in series connection. Always pay attention of the polarity of the secondary side. Keep the operating driver away from heat sources and use only in well ventilated places. Thermal protection: If the temperature exceeds the limit value, the driver switches itself off and after a few seconds on again. Avoid short circuit on the secondary side. Connect LEDs only when voltage is switched off. The connector terminals have to be tightened with care.
Connection cable on secondary side: Use a 0,5mm² to 1,5mm² cable with a length of maximum 10m.
Input cable: Use a H03VVH2F 2x0,75mm² cable.

Figure A.8: Datasheet of the power LED converter of the main light source [Con10].

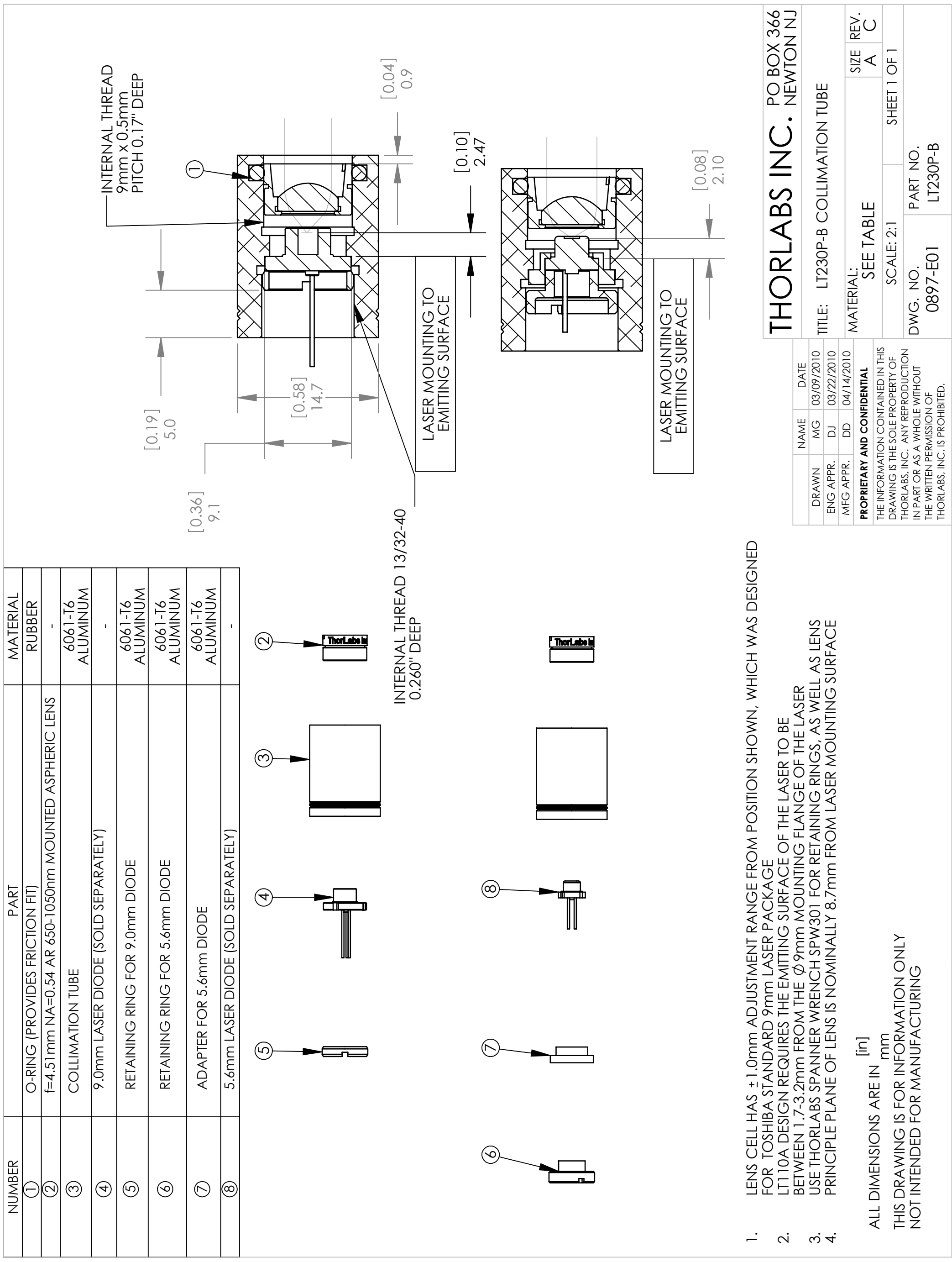


Figure A.9: Drawing of the collimator for the blue diode [Tho10a]

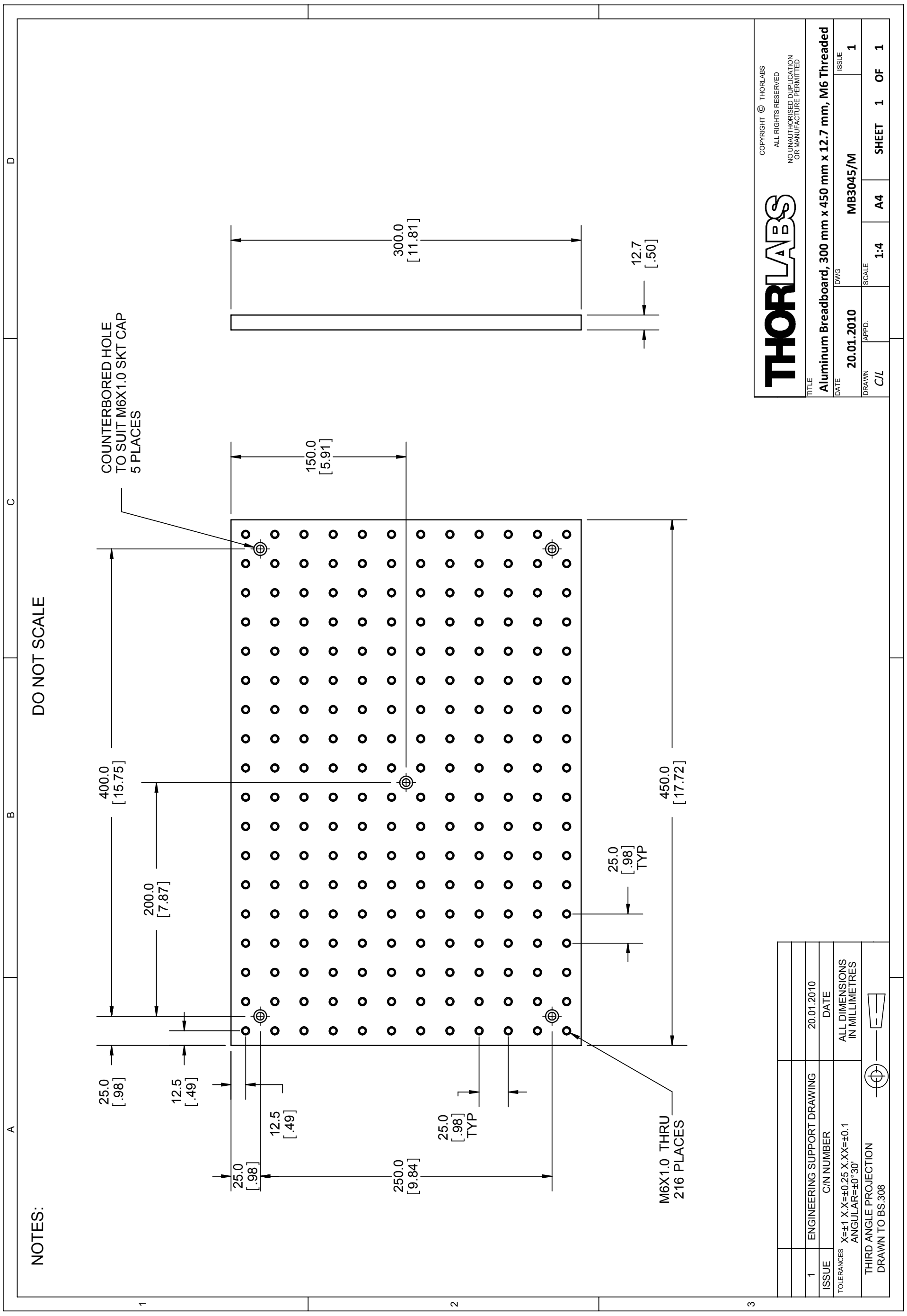


Figure A.10: Drawing of the anodized plate [Tho10c].

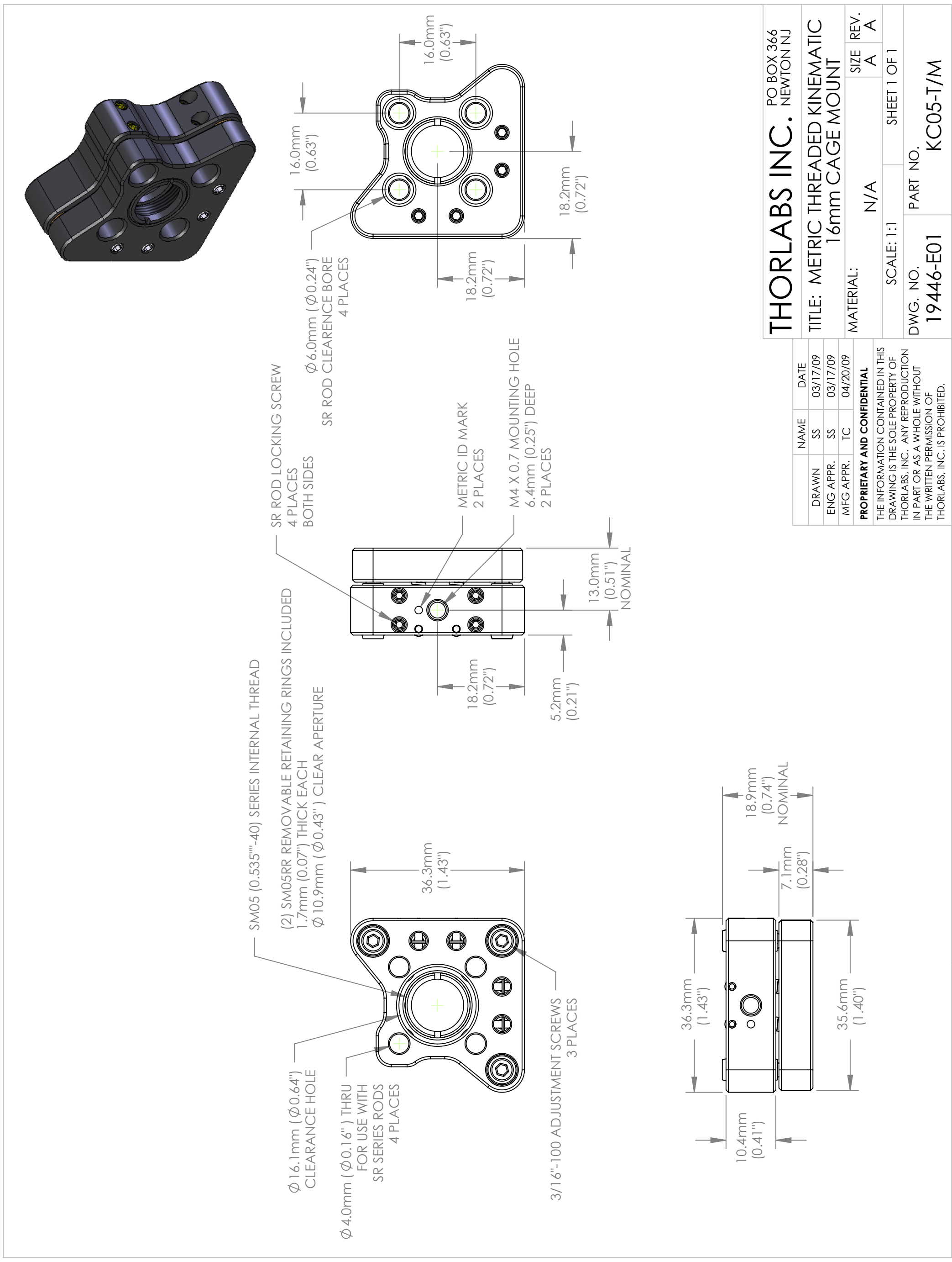


Figure A.11: Drawing of the kinematic mount for the alignment of the laser diodes in the reference light source [Tho10c].

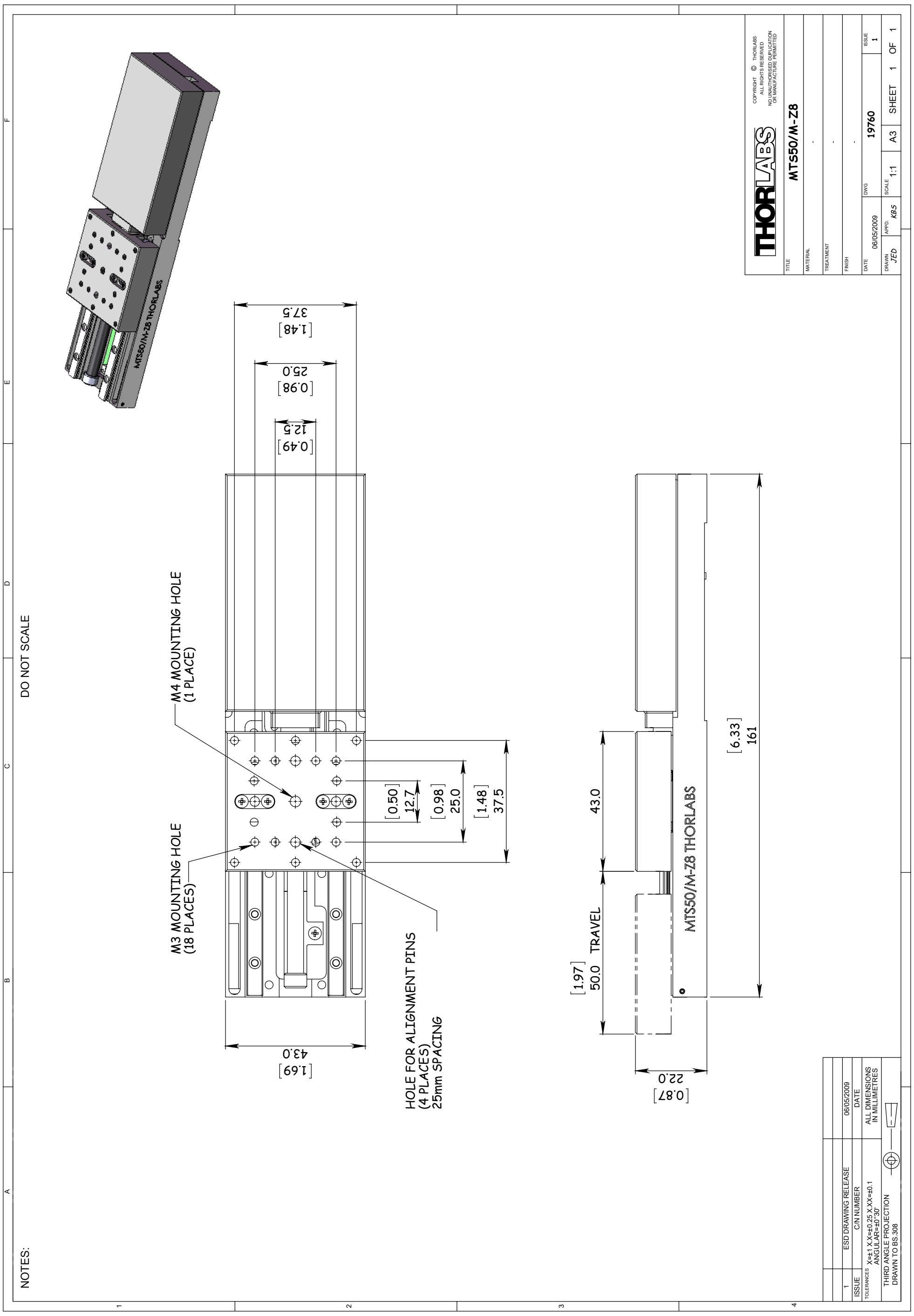


Figure A.12: Drawing of the translation stage [Tho10c].

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Ich versichere, dass ich die Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen uns Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

Aachen, den 19. Juli 2010