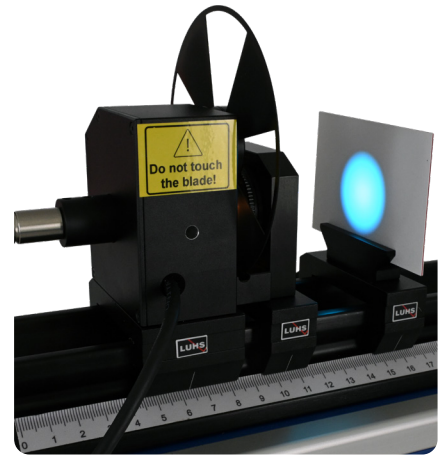
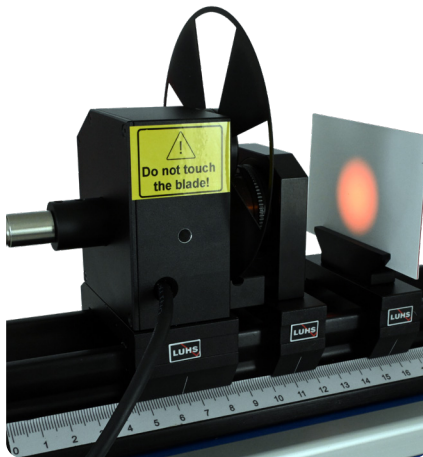
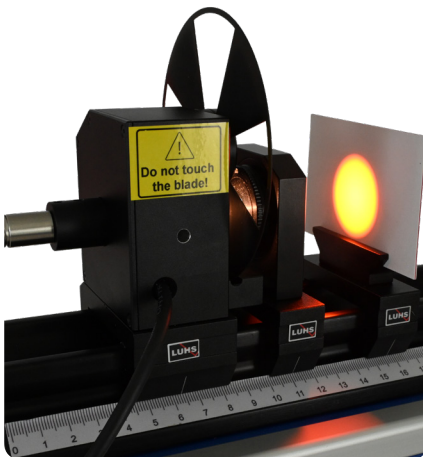
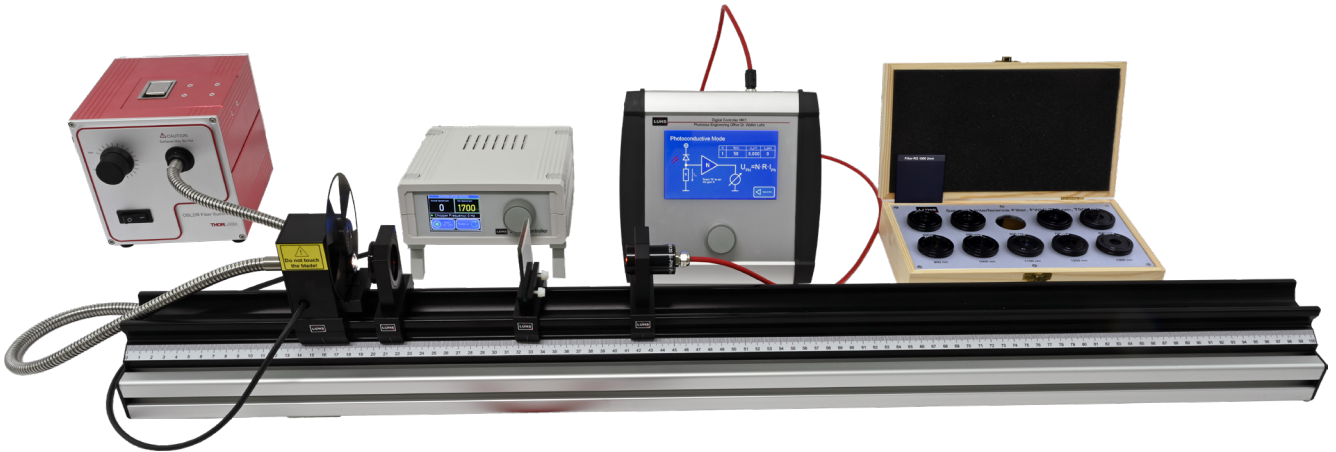


# PE-12 Detection of Light



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## 1.0 Introduction

Each application needs a detector to monitor the property of the used Laser as power, divergence, pulse shape, ...etc. Since Laser covers a manifold of different spectral lines ranging from UV up to IR, a particular detector with suited spectral response must be used for each spectral range. To obtain satisfactory results from your application other characteristics of the photodetector like sensitivity and time response should be taken into consideration. The ideal choice is a wavelength - independent detector which can detect very low as well as very high intensities with a very short response time, unfortunately this detector does not yet exist. Detection of light means converting photons to electrical signals that can be amplified and displayed, in other words, the photon detector can be considered as photon to electron transducer. Due to the manifold of the interaction with light and matter a number of different types of detectors are existing. Within this experimental set-up different photodetectors based on semi conduction and thermoelectric effects are investigated as these types are the most important ones used in industrial applications. For the characterization of the spectral sensitivity a combination of a white light lamp and 10 interference filter with a resolution of 10 nm and a range from 400 nm to 1300 nm is used. By means of a light chopper the time response of each detector can be measured. Especially for the semiconductor photo detector the influence of the outer electrical circuit on the response time and sensitivity will be determined. Since the set-up is provided with a tunable light source also other specimen having spectral characteristics like optical filter or mirror can be investigated also within this set-up. Before we re going to detect light the following chapters are giving a comprehensive overview of the properties and generation of light. After that, semiconductor photodiodes will be discussed and applied for the detection of light

## 2.0 Fundamentals

Light, the giver of life, has always held a great fascination for human beings. It is therefore natural that people have been trying to find out what light actually is, for a very long time. We can see it, feel its warmth on our skin but we cannot touch it.

The ancient Greek philosophers thought light was an extremely fine kind of dust, originating in a source and covering the bodies it reached. They were convinced that light was made up of particles.

As human knowledge progressed and we began to understand waves and radiation, it was proved that light did not, in fact, consist of particles but that it is an electromagnetic radiation with the same characteristics as radio waves. The only difference is in the wavelength.

We now know, that the various characteristics of light are revealed to the observer depending on how he sets up his experiment. If the experimentalist sets up a demonstration apparatus for particles, he will be able to determine the characteristics of light particles. If the apparatus is the one used to show the characteristics of wavelengths, he will see light as a wave. The question we would like to be answered is: What is light in actual fact?

The duality of light can only be understood using modern quantum mechanics. Heisenberg showed, with his famous

“Uncertainty relation”, that strictly speaking, it is not possible to determine the position  $x$  and the impulse  $p$  of a particle of any given occurrence at the same time.

$$\Delta x \cdot \Delta p_x \geq \frac{1}{2} \hbar$$

If, for example, the experimentalist chooses a set up to examine particle characteristics, he will have chosen a very small uncertainty of the impulse  $\Delta p_x$ . The uncertainty  $\Delta x$  will therefore have to be very large and no information will be given on the position of the occurrence. Uncertainties are not given by the measuring apparatus, but are of a basic nature. This means that light always has the particular quality the experimentalist wants to measure. We can find out about any characteristic of light as soon as we think of it. Fortunately the results are the same, whether we work with particles or wavelengths, thanks to Einstein and his famous formula

$$E = m \cdot c^2 = \hbar \cdot \omega$$

This equation states that the product of the mass  $m$  of a particle with the square of its speed  $c$  corresponds to its energy  $E$ . It also corresponds to the product of Planck's constant

$\hbar = \hbar \cdot 2\pi$  and its radian frequency  $\omega = 2\pi \cdot \nu$ , In this case  $\nu$  represents the frequency of luminous radiation.

## 2.1 Semiconductor and Photodiode

Within this project we are going to use different kind of photodiodes exploiting the properties of semi conducting solid state material to convert electrical current directly into light and vice versa. Nowadays nearly all electronically devices as transistors or integrated circuits are basing on this material and it is therefore useful to dedicate a chapter to their fundamentals. We want to know especially how light is generated and how it is absorbed to understand the concept of the photodetector.

We start with two separate atoms and describe the change of their energy states when they are approaching each other. In a next step the number of atoms is increased and the appearance of energy bands will be discussed. The choice and combination of different semi conducting materials finally decides upon whether a LED, photodetector or a Laser diode can be realized.

## 2.2 The energy band model

Atoms or molecules at a sufficient large distance to their neighbors do not notice mutually their existence. They can be considered as independent particles. Their energy levels are not influenced by the neighboring particles. The behavior will be different when the atoms are approached as it is the case within a solid body. Depending on the type of atoms and their mutual interaction the energy states of the electrons can change in a way that they even can abandon „their“ nucleus and move nearly freely within the atomic structure. They are not completely free, otherwise they could leave the atomic structure.

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

will fail latest when we try to justify the existence of solid Argon just by freezing it sufficiently. Since there is obviously some sort of binding within the crystal structure in spite of the fact that inert gases are neutral there must be additional forces which are responsible for this binding. To understand these forces we must call on quantum mechanics for help. Here we can only summarize as follows:

If atoms are mutually approached the states of the undisturbed energy levels split into energetically different states. The number of newly created energy states are corresponding to the number of exchangeable electrons (Fig. 1).

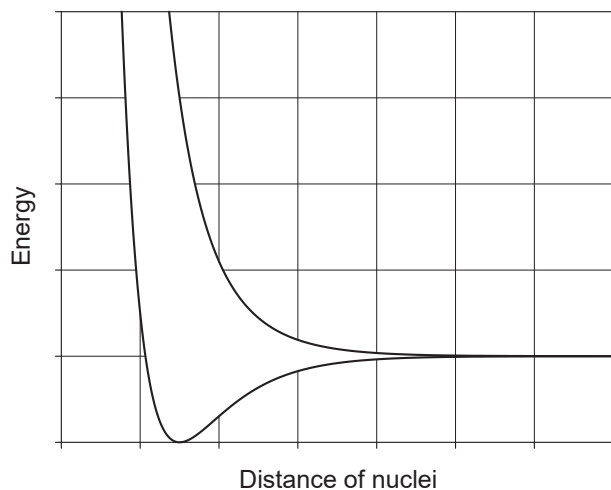


**Fig. 1: Potential energy due to interaction of two hydrogen atoms**

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

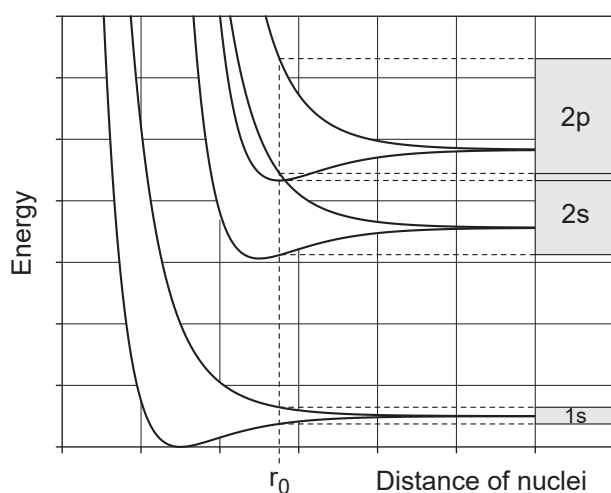


**Fig. 2: Band formation by several electrons. The most outside electrons are responsible for the equilibrium distance  $r_0$ .**

It is easy to imagine that an increase of the number of atoms also increases the number of exchangeable electrons and in consequence also the number of newly generated energy levels. Finally the number of energy levels is so high and so dense that we can speak about an energy band. Here it is

interesting to compare the action of the electrons with the behavior of ambassadors:

The electrons in the most outside shell of an atom will learn first about the approach of an unknown atom. The eigenfunctions will overlap in a useful way. One electron will leave the nucleus tentatively to enter an orbit of the approaching atom. It may execute a few rotations and then return to its original nucleus. If everything is OK and the spins of the other electrons have adapted appropriate orientation new visits are performed. Due to the visits of these „curious“ electrons the nuclei can continue their approach. This procedure goes on till the nuclei have reached their minimum of acceptable distance. Meanwhile it can no more be distinguished which electron was part of which nucleus. If there is a great number of nuclei which have approached in this way there will also be a great number of electrons which are weakly bound to the nuclei. Still, there is one hard and fast rule for the electrons: I will only share my energy level by one electron with opposite spin (Pauli principle). Serious physicists may now warn to assume that there may be eventually male and female electrons. But who knows.....

Let's return to incorruptible physics.

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

In the following section the question is to be answered how the density of states of a band of electrons looks like and on which quantities it depends. After all this information will explain the emission or absorption of light photons due to electron transitions inside these bands.

## 2.3 Fermi distribution

In Fig. 1 we have shown that the energy bands are the result of the mutual interaction of the atoms. Each band has a particular width  $\Delta E$ , the magnitude of which is determined by the exchange energy and not by the number  $N$  of the interacting atoms. Furthermore we know that the number of energy levels within a band is determined by the number of interacting electrons. The Pauli principle states that such a level can only be occupied by two electrons. In this case the spins of the electrons are anti parallel. Within a band the electrons are free to move and they have a kinetic energy. The maximum energy  $E_{\max}$  of an electron within a band can not pass the value  $\Delta E$  since otherwise the electron would leave the band and no longer be a part of it.

The famous physicist Enrice Fermi calculated the theoretical energy distribution and how many electrons of energy  $E \leq E_{\max}$  exist in the energy interval  $dE$ .

$$\frac{dn}{N} = \frac{\sqrt{8/\pi}}{\sqrt[3]{k^2 T^2}} \sqrt{E} \cdot e^{-\frac{E}{kT}} \cdot dE$$

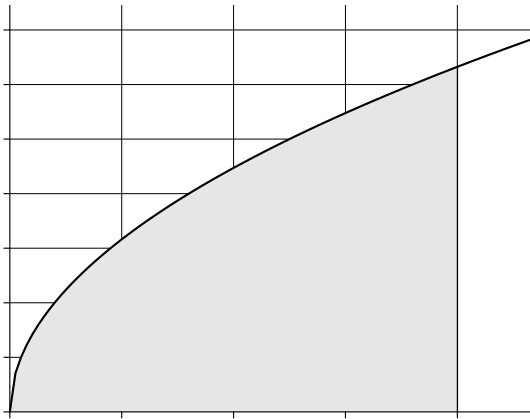


**Fig. 3:** Number of electrons per unit volume  $V$  and energy interval  $dE$  as a function of the energy  $E$ .

The situation in Fig. 3 shows that the band has not been completely filled up since the Fermi energy is smaller than the maximal possible energy. This means that this band is a conduction band. If the Fermi energy would be equal to the maximal energy we would have a valence band. A transfer of this knowledge to the energy level scheme of Fig. 2 and a selection of the 2s band would provide the picture of Fig. 4.

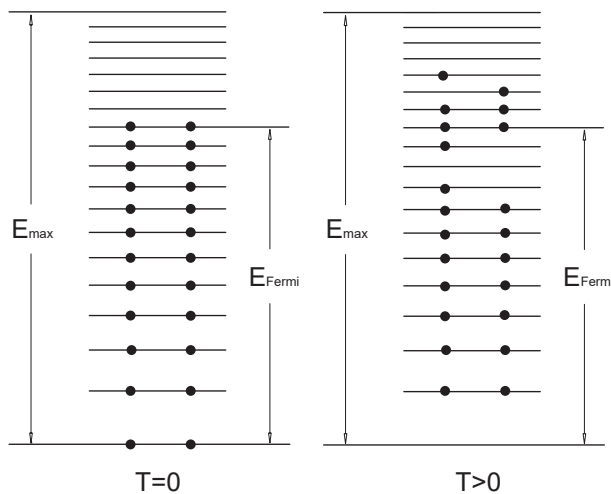


**Fig. 4:** Distribution of free electrons over the energy states within a conduction band

Up to this point we anticipated that the temperature of the solid body would be  $0^\circ \text{K}$ . For temperatures deviating from this temperature we still have to respect thermodynamic aspects namely additional energy because of heat introduced from outside.

Fermi and Dirac described this situation using statistical methods. The electrons were treated as particles of a gas: equal and indistinguishable. Furthermore it was presumed that the particles obey the exclusiveness principle which means that any two particles can not be in the same dynamic state and that the wave function of the whole system is anti symmetrical.

Particles which satisfy these requirements are also called Fermions. Correspondingly all particles which have a spin of  $1/2$  are Fermions and obey the Fermi Dirac statistics. Electrons are such particles.

Under respect of these assumptions both physicists got the

following equation for the particle density  $dn(E)$  of the electrons within an energy interval  $dE$ :

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

The equation above is illustrated by Fig. 5.

As shown in Fig. 4 by introduction of thermal energy the „highest“ electrons can populate the states which are above them.

Based on these facts we are well equipped to understand the behavior of solid bodies. We are going to concentrate now our special interest on the semiconductors which will be presented in the next chapter with the help of the previously performed considerations.

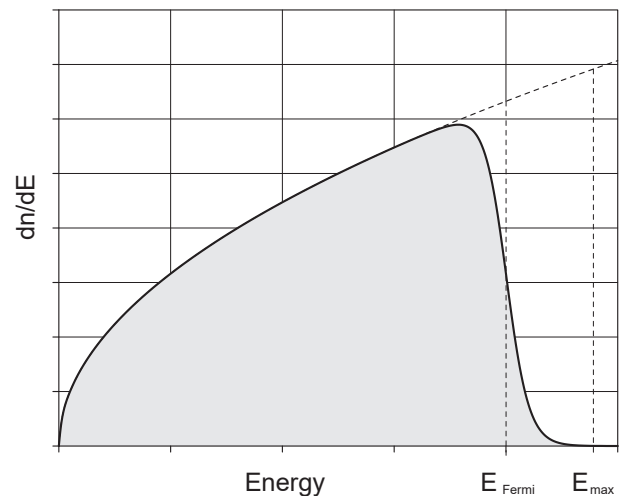


**Fig. 5:** Number of electrons per unit volume and energy interval  $dE$  as a function of the energy  $E$ , but for a temperature  $T > 0$ .

## 2.4 Semiconductors

Before starting the description of the semiconductor with regard to its behavior as „light emitting and absorbing“ medium we still have to study the „holes“. States of a band which are not occupied by electrons are called „holes“. Whenever an electron leaves its state it creates a hole. The electron destroys a hole whenever it occupies a new state. The whole process can be interpreted in that way that the hole and the electron exchange their position (Fig. 6). Also the holes have their own dynamic behavior and can be considered as particles like the electrons.

It is interesting to note that the holes do have the exact opposite properties of the electrons. Since the temporary course of the holes' migration is the same as for the electron they have also the same mass except that the mass of the hole has the opposite sign. Furthermore its charge is positive.

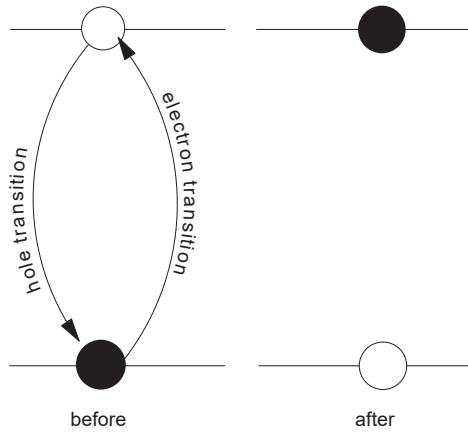


**Fig. 6: Electron and hole transition**

Once the existence of the holes has been accepted they also have to have a population density. It will be introduced in the following. For this reason we complete Fig. 4 as shown in Fig. 7.

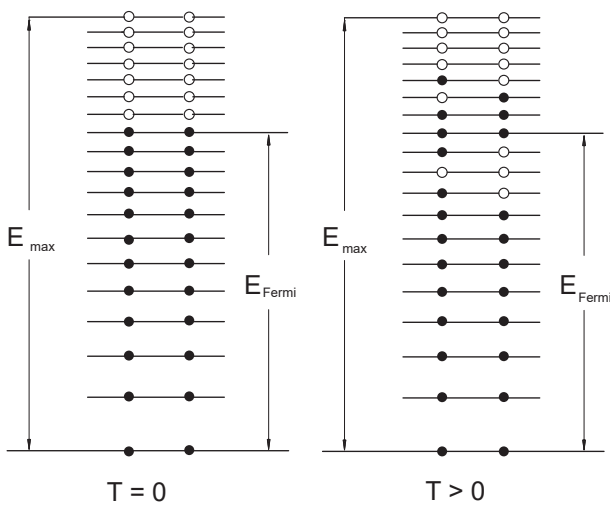


**Fig. 7: Distribution of the holes and the electrons within an energy band**

It is easy to understand that on one side the holes are preferably at the upper band edge and on the other side their population density results out of the difference of the population density minus the population density of the electrons. Fig. 8 shows the population density of the electrons. Fig. 9 shows the difference and in so far the population density of the holes. Attention has to be paid to the fact that the abscissa represents the energy scale of the band and not the energy of the holes.

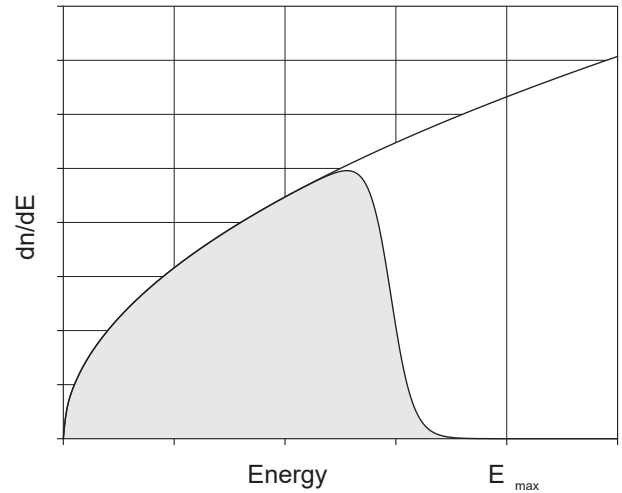


**Fig. 8: Population density of the electrons**

To prepare the discussion of optical transitions in semiconductors it gives a sense to modify the diagrams. Until now the abscissa was used as energy scale for the diagrams of the state and population densities. For the presentation of optical transitions it is more practical to use the ordinate as energy scale. To get use to it Fig. 8 has been represented in the modified way in Fig. 10. The shown population density refers to an energy scale for which the lower edge of the valence band has been set arbitrarily to zero. The represented situation refers to a semiconductor where the distance between conduction and valence band is in the order of magnitude of thermal energy ( $kT$ ). Here the Fermi energy lies in the forbidden zone.

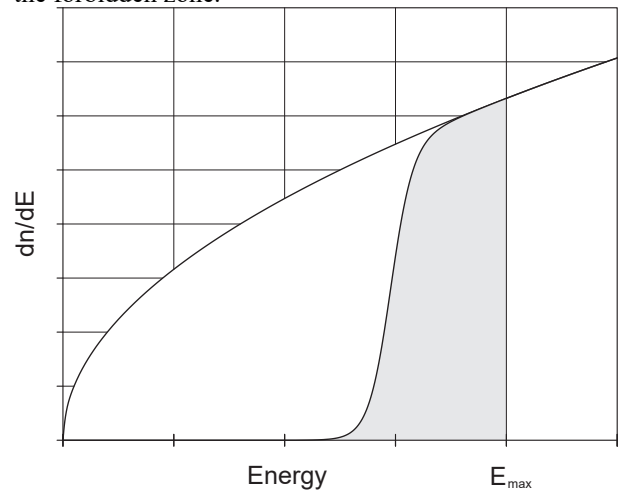


**Fig. 9: Population density of the holes**

Because of the thermal energy some electrons have left the valence band and created holes. For the following considerations it is sufficient to learn something about the population densities of the electrons in the conduction band as well as about the holes in the valence band. As will be shown later there are optical transitions from the conduction band to the valence band provided they are allowed. Near the lower band edge of the conduction band the state densities are admitted to be parabolic. The same is true for the holes at the upper edge of the valence band (Fig. 11). The densities of states inform about the number of states which are disposed for population and the spectral distribution reflects how the electrons and holes are distributing over these states. Next to the band edges the spectral distribution fits to a Boltzmann distribution.

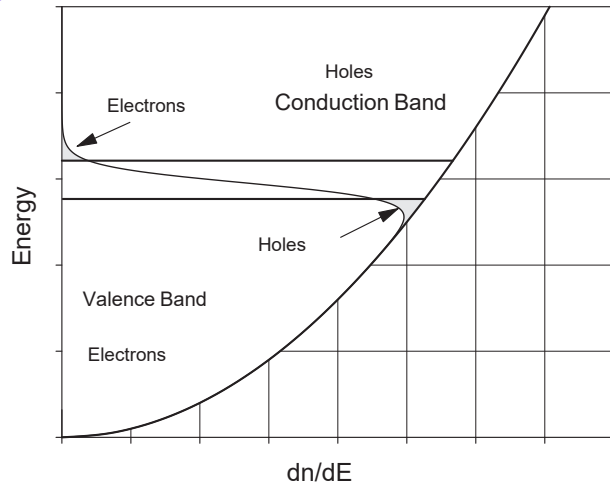


**Fig. 10: Population density on the energy scale**

If we succeed to populate the conduction band with electrons and to have a valence band which is not completely occupied by electrons (Fig. 11) they may pass from the conduction band to the valence band. That way a photon is generated. By absorption of a photon the inverse process is also possible.

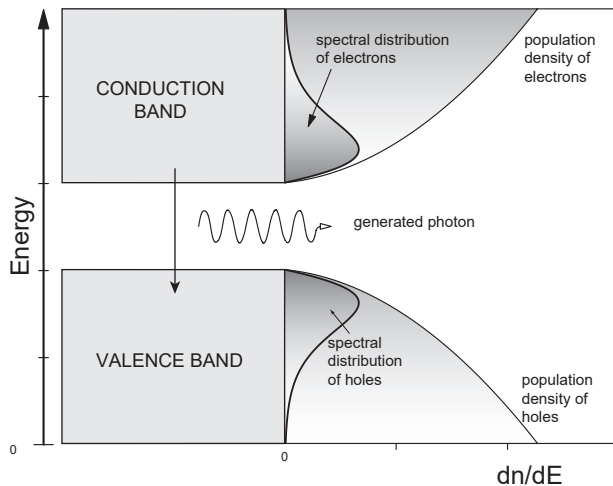


**Fig. 11: Densities of states and spectral distributions**

If a transition from the conduction to the valence band takes place, a photon is generated. However, if a photon enters the structure an electron will be lifted from the valence to the conduction band.

## 2.5 Photodetector

Semiconductor pn transitions with a band gap of  $E_g$  are suitable for the detection of optical radiation if the energy  $E_p$  of the photons is equal or greater than the band gap. In this case an incident photon can stimulate an electron to pass from the valence band to the conduction band (Fig. 12). Here three types of events are possible:

- An electron of the valence band in the p-zone is stimulated and enters the p-zone of the conduction band. Because of the external electric field due to the voltage  $V$  it will diffuse through the pn-junction area into the n-zone and contributes to the external current passing the resistor  $R_L$  unless it recombines in the p-zone.
- If an electron of the pn-junction is hit by a photon the generated hole will migrate into the p-zone and the electron into the n-zone. The drift of both charges through the pn

- junction causes a current impulse. The duration of the impulse depends on the drift speed and on the length of the pn-zone.

C. The case is similar to case A. The hole migrates due to the presence of the external field into the p-zone or recombines in the n-zone.

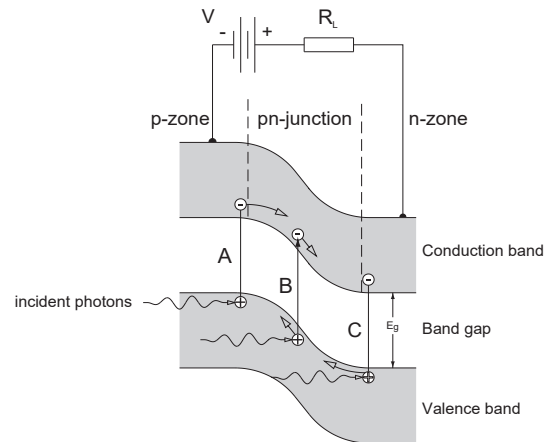


**Fig. 12: Absorption of a photon with subsequent transition of the stimulated electron from the valence band to the conduction band**

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

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

At a light energy of  $P_0$  a number of

$$\frac{P_0}{\hbar\omega}$$

photons will hit the detector as  $\hbar\omega$  is just the energy of a single photon. But only that fraction of photons is converted into current pulses which is absorbed in the area of the pn-zone. This fraction may be called  $\eta P_0$ , where  $\eta$  is called quantum efficiency. The number of generated current pulses or the production rate therefore will be

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

and the average photo current:

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

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

- Diffusion current, it is created because of statistical oscillations of the charge carriers within the diffusion area
- Regeneration or recombination current, it is generated by random generation and annihilation of holes
- Surface currents, which are hardly avoidable since the

ideal insulator does not exist

4. Avalanche currents are flows of electrons which appear at high electric field strengths, if, for example, a high voltage is applied to the photodiode

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

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

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

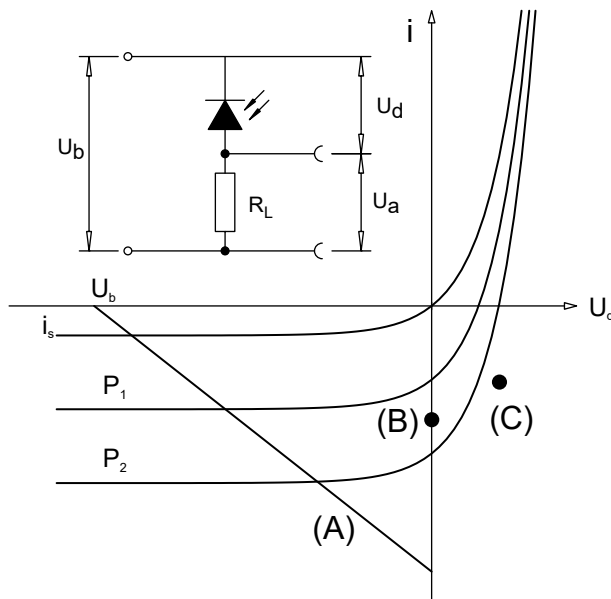


**Fig. 13: Characteristic curve (A) of a photodiode in the photoconductive mode, (current mode: B and photovoltaic: C)**

In principle a photodiode can be used in three different modes, the photoconductive, the current and photovoltaic mode. For the detection of fast and weak signals the photoconductive mode is suited as best (Fig.13 A). In this mode the diode is provided with a bias  $U_b$  reducing the pn junction capacity thus increasing the cut off frequency.

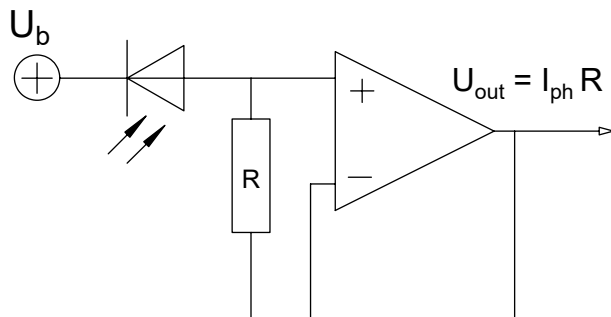


**Fig. 14: Photodiode used in Conductive Mode**

If fast light signals with medium strength photodiodes are used in connection with transimpedance amplifier. In this case the photodiode is driven in the current mode (Fig. 13 B).

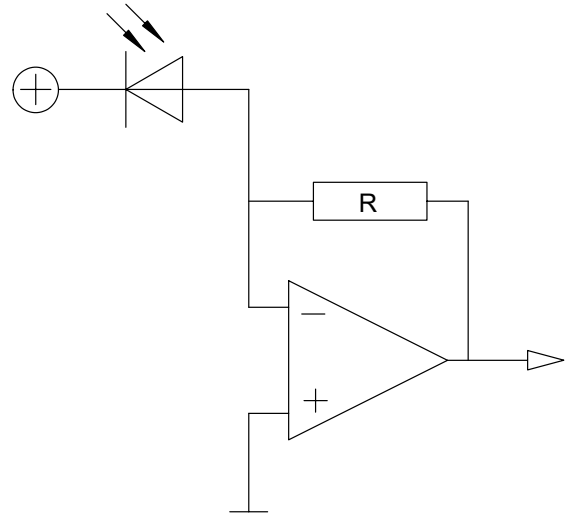


**Fig. 15: Current Mode Operation with Transimpedance Preamplifier**

In this case the photodiode is driven in short-cut mode with  $U_d$  nearly equal zero. This mode requires the preamplifier to be used in transimpedance mode for which the input impedance can be fit to the photodiode. This mode, also termed as current to voltage converter, allows a low input impedance even for high gain.

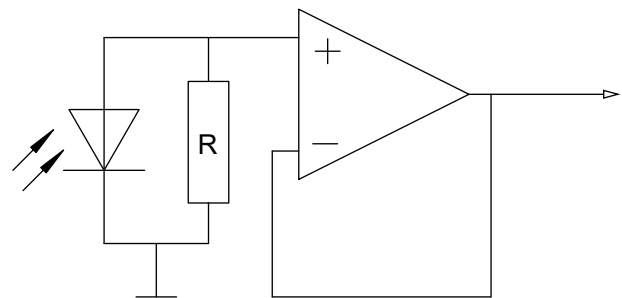


**Fig. 16: Photovoltaic Mode (C)**

There is also a third operational mode designed specifically for detecting intensities that are low and change slowly. A good detector for optical communication technology is characterized by the fact that it is very fast (up to the GHz range) and that it has a high quantum efficiency which means that it is very sensitive. Depending on the wavelength range which has to be covered by the detector one uses silicon or germanium semiconductor material for the construction of the detectors.

### 2.5.1 Ge and Si PIN photodiodes

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

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

One recognizes that for large wavelengths the energy of the photon may no more be sufficient „to lift“ the electron in a way that it passes the band gap. For smaller wavelengths one has to respect that the conduction band and also the valence band have upper edges which is followed by a band gap.

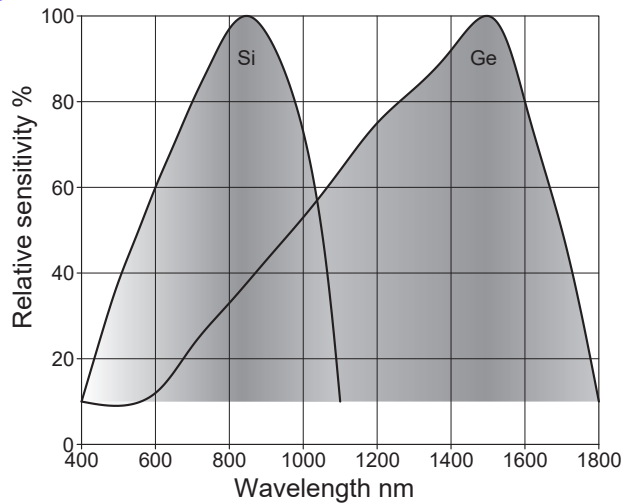


**Fig. 17: Spectral sensitivity curves of Si and Ge photodiodes**

Photons having energies exceeding the upper limit of the conduction band can no more be absorbed. The wavelength of the applied light source decides which detector material is to be used. For wavelengths above 1  $\mu\text{m}$  up to 1.5  $\mu\text{m}$  Germanium is recommended. Below these values Silicon detectors are used. In the present experiment LED's of 520 and 630 nm wavelength are applied. Therefore a silicon detector is used. To get a high quantum efficiency not a PN but a PIN detector has been chosen.

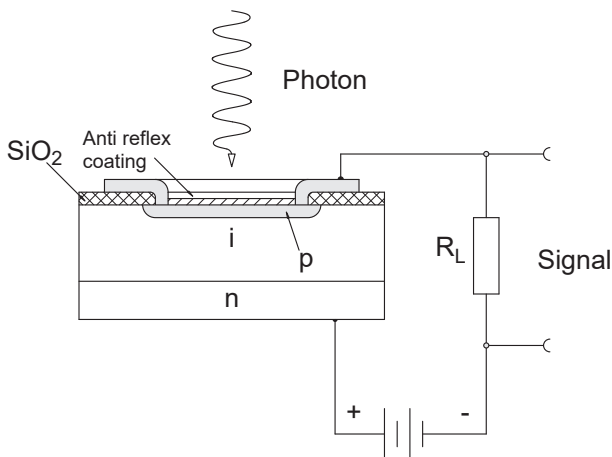


**Fig. 18: Design of a PIN detector**

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

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

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

## 2.5.2 Thermopile Detector

A thermopile is a series of thermocouples built on a microchip. One inner set of the thermocouple junctions (Fig. 2.19) is thermally isolated and exposed to the to be measured radiation whereas the outer set is heat sunk to the package.

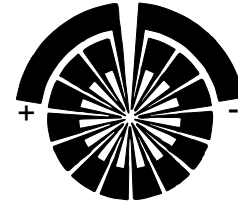


**Fig. 19: Optical Thermopile Detector**

If light hits the center of the detector, it is absorbed and increases the temperature difference between the inner and outer thermocouple junctions resulting in the generation of a thermocouple voltage. The amplitude increases with the number of thermocouples used. Typically these are 15 covering an active area of 1  $\text{mm}^2$ .

The great advantage of this kind of detectors lies in its wavelength independence and can therefore be used for the power measurement of light with different wavelength. However such detectors have a low frequency response and cannot be used above 10 Hz.

Within this project it is of importance to know the relative spectral power of the light source used.

### 3.0 Description of the Modules

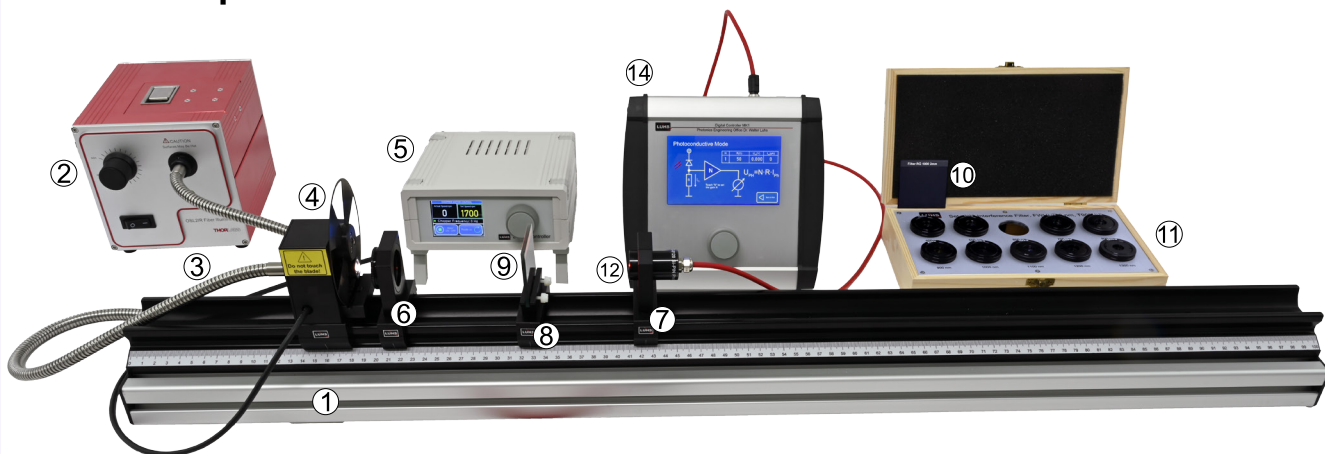
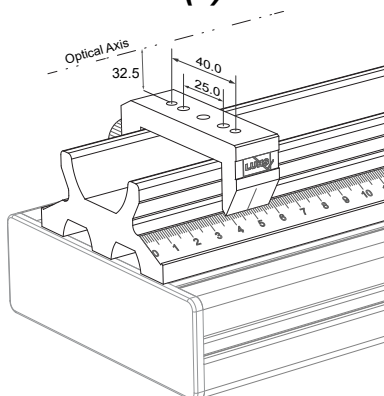


**Fig. 20: Experimental set-up**

- |                                                                        |                                                                          |
|------------------------------------------------------------------------|--------------------------------------------------------------------------|
| 1 MP-0100 Optical Bench MG-65, 1000 mm                                 | 8 MM-0220 Screen holder mounted on carrier MG20                          |
| 2 Thorlabs' OSL2IR Fiber-Bundle-Coupled Tungsten-Halogen Light Sources | 9 OC-0910 Filter KG5, 50 x 50 x 3 mm                                     |
| 3 Fiber Bundle                                                         | 10 4F-0010 Colored glass filter RG1000, 50 x 50 x 3 mm                   |
| 4 MM-0600 Light chopper on MG65                                        | 11 OC-DL10 Set of 10 Bandpass filter 400 - 1300 nm step 100 nm, BW 10 nm |
| 5 DC-0900 Chopper controller                                           | 12 DC-0120 Si-PIN Photodetector, BPX61                                   |
| 6 MM-0030 Mounting plate C30                                           | 13 DC-0160 InGaAs Photodetector                                          |
| 7 MM-0020 Mounting plate C25 on carrier MG20                           | 14 DC-0370 Photodetector Connection Device                               |

#### 3.1 Optical Bench(1)



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

#### 3.2 Tungsten-Halogen Light (2)

Thorlabs' OSL2IR Fiber-Bundle-Coupled Tungsten-Halogen Light Sources deliver white light for brightfield microscopy, laboratory, and illumination applications. The output illumination intensity is exponentially variable from 0 to 100% using a knob on the front of the unit.



The 150 W EKE halogen bulbs have a 3200 K color temperature and are user replaceable with optional bulbs. These portable fiber-coupled light sources are compatible with 100 to 120 VAC as well as 220 to 240 VAC and includes a location-specific power cord.

A 91 cm (36") long fiber bundle with a Ø6.4 mm (Ø0.25") effective core is included with the OSL2IR light sources. The fiber illuminator's output port also has internal, 3.5 mm deep SM1 threads. The unit is shipped with a fiber bundle adapter installed in these threads.

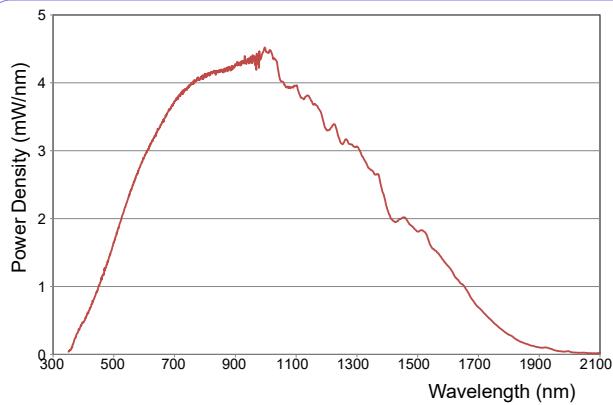


**Fig. 21: Spectral Output Power of the Halogen lamp including the spectral attenuation of the glass fiber bundle.**

These spectra represent the output of the OSL2B bulb installed in the OSL2BIR bulb installed in the OSL2IR light source (red line). The OSL2BIR bulb has an aluminum-coated reflector for enhanced performance in the infrared. These spectra are taken with the included fiber bundle and account for attenuation within the fiber bundle



This focusing packages is designed for use with the fiber bundle included with the OSL2IR light sources. Two 6-32 setscrews that accept a 1/16" hex key secure the tip of the fiber bundle into the back of the collimation or focusing package.



**Fig. 22: The light output from the fiber bundle included with the OSL2 lamp. It show the beam when the focusing packages is attached.**

Insert the focusing unit into the opening in the mechanical copper. The unit must not touch the chopper blade. Once in the correct position, secure the unit with the locking screw.

### Light chopper (4)



In module 4, a chopper blade is driven by an electrical motor which switches the passing light periodically on and off. This unit is used to measure the time response of the detector to be characterized. Furthermore it is used to suppress unwanted environmental stray light which did not pass the chopper. For this purpose the assembly is provided with a photoelectric switch which signal is used for synchronization of the subsequent detection system. The chopper is mounted on a carrier. To control the speed of the chopper controller DC-0090 is used. The synchronization signal is available at the BNC socket.

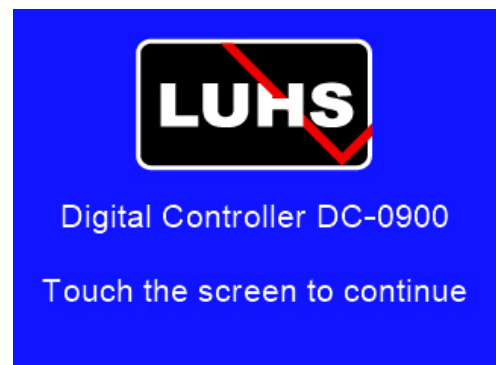
### 3.3 Chopper controller (5)



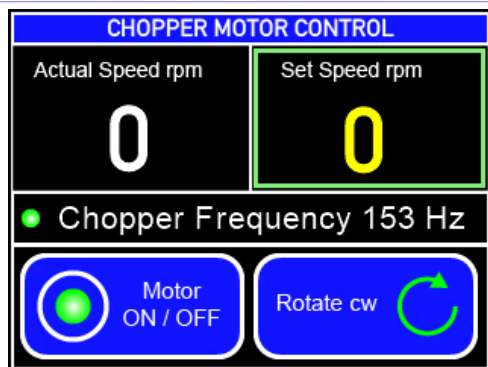
The chopper controller includes a DC motor driver to adjust the rotational speed of the motor and, consequently, the chopper blade. The chopper is equipped with a photoelectric sensor that measures the rotational speed or frequency.



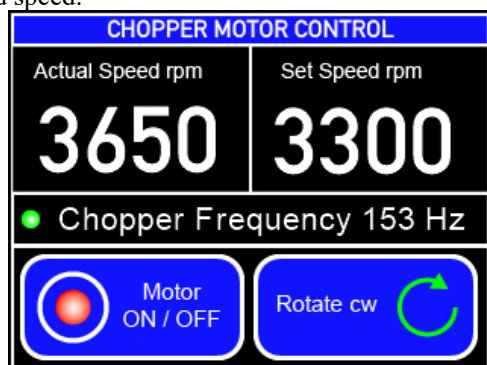
The chopper is connected to the controller via a 9-pin Sub-D connector. The signal from the light barrier is available at the BNC jack. The device is powered by the included 12 VDC power supply.



After turning on the device, the startup screen appears. Tap the screen to access the main screen.

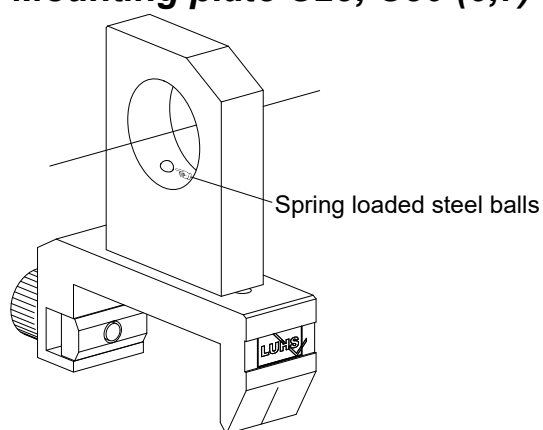


When you tap the “Set Speed rpm” field, it becomes high-lighted. You can now use the adjustment knob to select the desired speed.



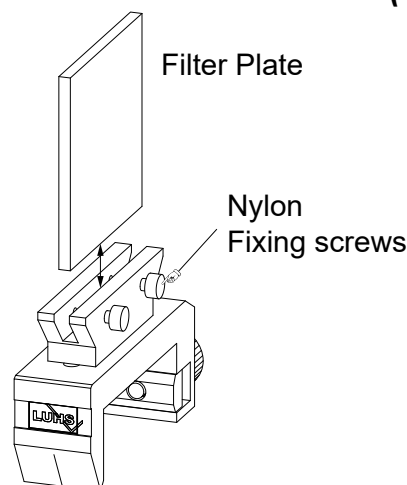
Pressing the Motor ON/OFF button turns the chopper motor on or off. Due to the inertia of the chopper blade, it takes a while for the desired speed to be reached. Pressing the Rotate cw button allows you to select the direction of rotation.

### 3.4 Mounting plate C25, C30 (6,7)



This frequently used component is ideal to accommodate parts with a diameter of 30 or 25 mm where it is kept in position by three spring loaded steel balls. Especially C25 or C30 mounts having a click groove are firmly pulled into the mounting plate due to the smart chosen geometry. The mounting plate is mounted to a 20 mm wide carrier.

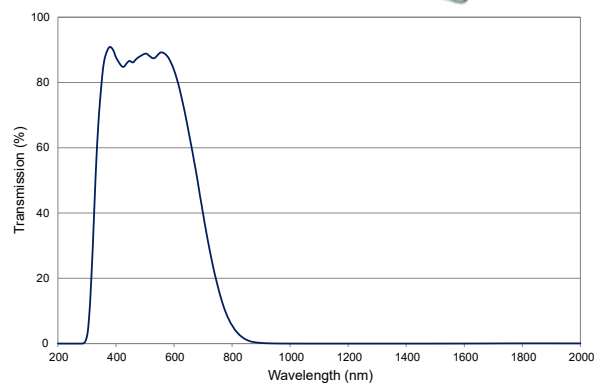
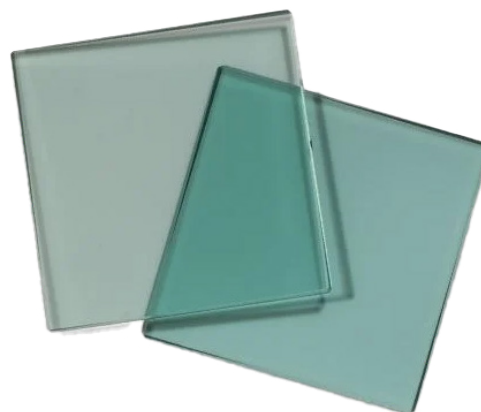
### 3.5 Screen holder on carrier (8)



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 grub nylon knurled screws.

### 3.6 Filter KG5, 50 x 50 x 3 mm (9)

KG colored glass, which offers excellent absorption of infrared radiation, is used for heat-absorbing short-pass filters made of colored glass. These filters are also well-suited for use as short-pass filters, as they transmit visible wavelengths while blocking infrared radiation. Heat-absorbing short-pass filters made of colored glass are ideal for protecting sensitive components from the heat generated by high-intensity lighting systems.



### 3.7 Colored glass filter RG1000 (10)

The colored glass filter RG1000, which is 3 mm thick, operates as a long pass filter permitting transmission of wavelengths above 1000 nm.

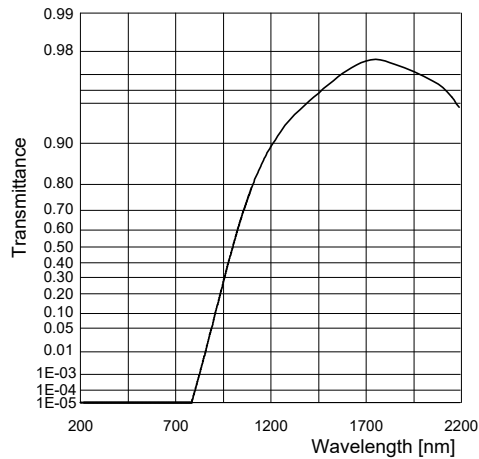


Fig. 23: Transmission curve of the RG1000 filter, 3 mm thick

### 3.8 Set of 10 Bandpass filter (11)



Fig. 24: Set of 10 Interference filter

A set of 10 interference filters ranging from 400 nm to 1300 nm is used to generate a specific wavelength. If such a filter is placed in the beam path of the white-light lamp, a 10-nm narrow-band emission is obtained. A total of 10 wavelengths are then available for measuring filters or the spectral sensitivity of photodetectors. The filters are mounted in a C30 holder and inserted into the corresponding mounting plate, where they are held in place by spring-loaded balls.

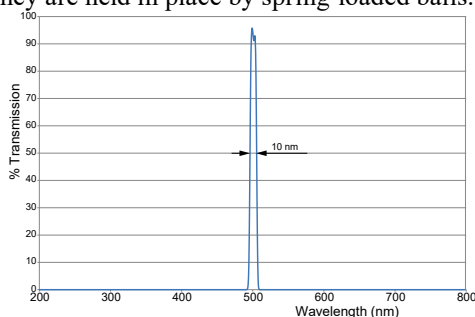


Fig. 25: Example of the 500 nm filter

The Fig. 25 shows the transmittance of the 500 nm filter as representative of all other filters. The emission bandwidth is 10 nm for all filters.

### 3.9 Si-PIN and InGaAs Photodetector (12,13)



The InGaAs FGA10 photodiode (13) is ideal for measuring both pulsed and CW light sources, by converting the optical power to an electrical current. The detector is a TO-5 package with an anode, cathode, and case and is mounted into a C25 housing. The photodiode anode produces a current, which is a function of the incident light power and the wavelength. The responsivity  $S(\lambda)$ , is subject of the measurements.

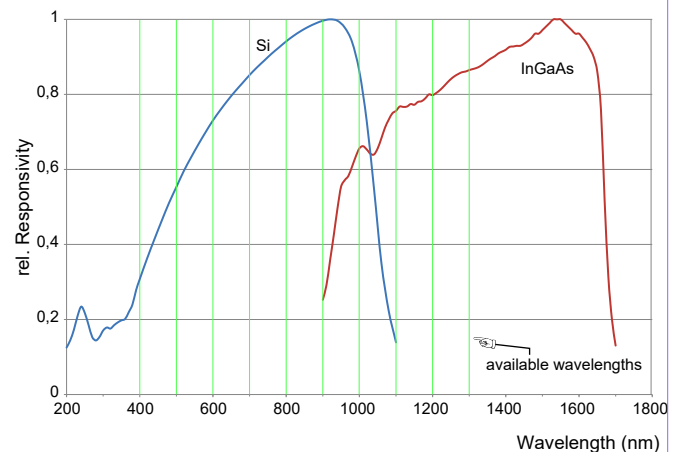


Fig. 26: Spectral sensitivity curves ( $S(I)$ ) for Si and InGaAs detectors. The green lines indicate the available wavelength

The Si detector is housed in the same enclosure as the InGaAs detector and is equipped with a connection cable for connecting to the photodetector connection device.

### 3.10 Photodetector Connection Device (14)

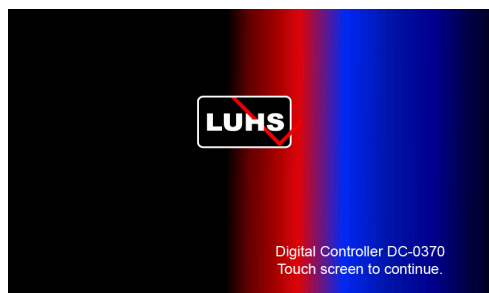


The device contains the electronics for a transimpedance amplifier and for the photoconductive mode.

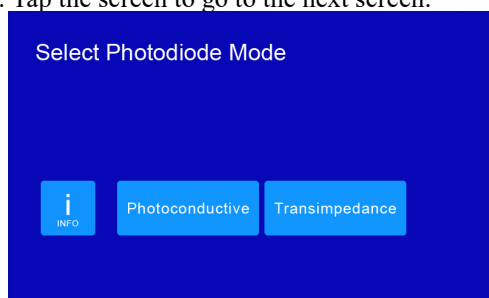


Fig. 27: The back of the device

The diode—whether Si or InGaAs—is connected to the device via the 3-pin input jack. The analog signal generated is available at the “PD-OUT” BNC connector for further use. The device is powered by the included power supply, which provides 12 volts of DC voltage.



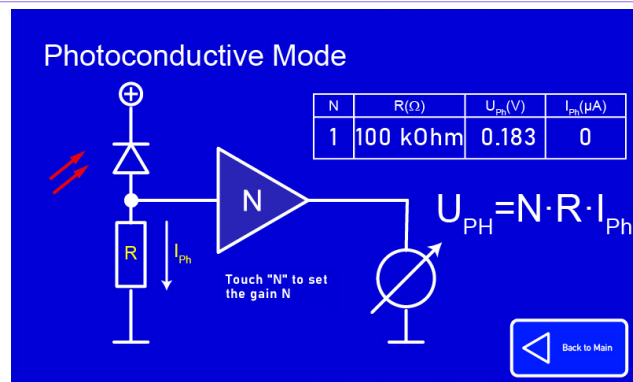
The home screen appears immediately after turning on the device. Tap the screen to go to the next screen.



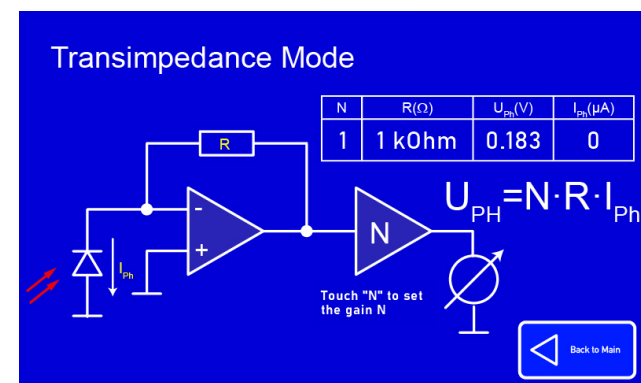
On the home screen, there are three buttons that open the Info screen, the Photoconductive Mode screen, or the Transimpedance control screen.



A QR code is available on the information screen in case further contact is needed.



In photoconductive mode, the cathode of the photodiode is connected to a 5 V voltage source and to ground via a resistor R. The photocurrent  $I_{ph}$  creates a voltage drop across the resistor R. This resistor is adjusted to a desired value between 10 Ohms and 50 kOhms using the control knob. The gain of the analog-to-digital converter can be set to 1, 2, 4, or 8 by touching the screen. The value of the selected resistance and the gain are displayed, as are the measured photocurrent and the calculated photocurrent.



In transimpedance mode, the cathode of the photodiode is connected to the inverting input of the operational amplifier, and the anode is connected to ground. The output voltage is proportional to the feedback resistance R and the gain of the analog-to-digital converter. The adjustment knob can be used to set resistance R values of 1, 10, 100 kOhm, and 1 MOhm and 10 MOhm.

## 4.0 Measurements

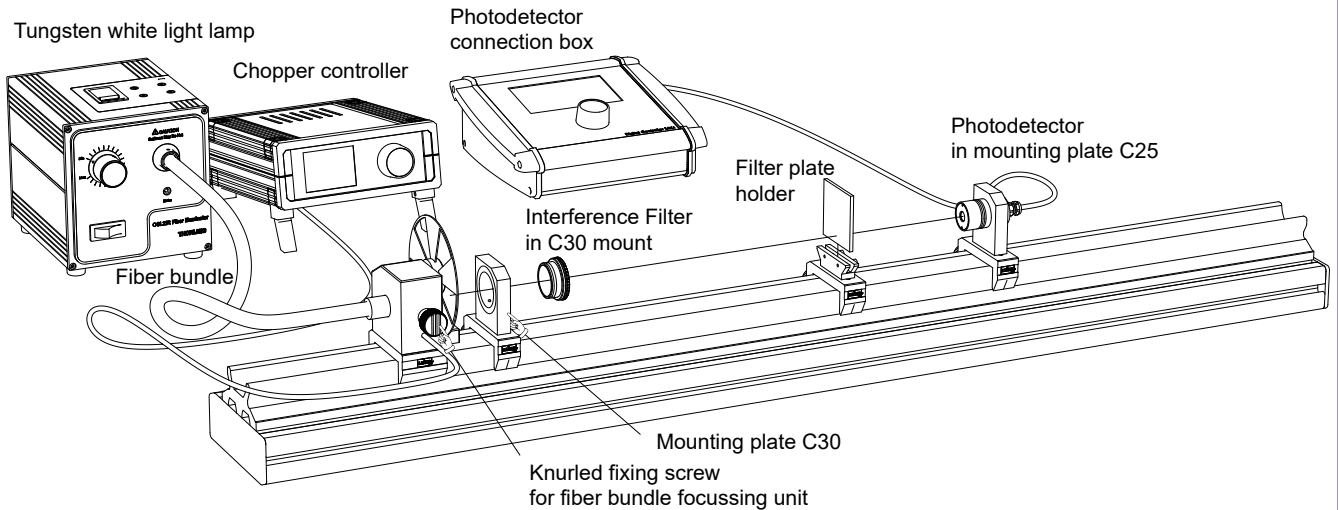


Fig. 28: Overview of the components required for the following experiments and measurements

The experiments begin with the verification of the  $1/r^2$  inverse-square law. Once a certain level of experience has been gained, the sensitivity curves of the Si and InGaAs photodetectors are recorded. Using the data obtained in this

way, the transmittance curves of the KG5 and RG1000 filters are determined in the next experiment. Finally, in the last experiment, the dynamic behavior of one of the detectors—or both—is measured using an oscilloscope.

### 4.1 Verification of the $1/R^2$ Law

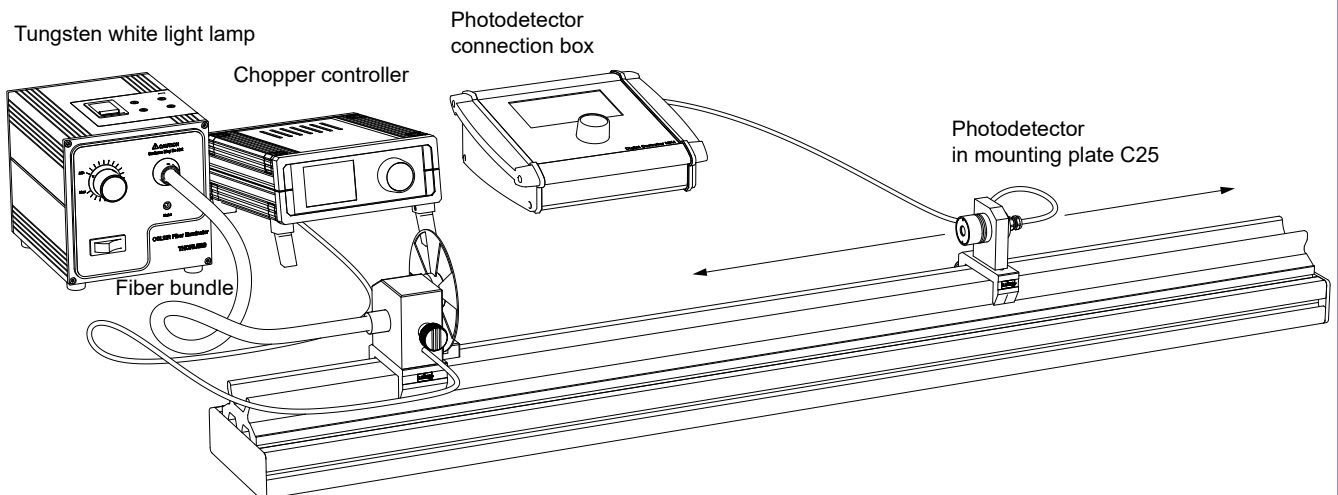


Fig. 29: Experimental setup for determining the  $1/r^2$  inverse-square law

For this measurement task, we need the white light source, which is connected to the light chopper via its fiber bundle and focusing optics. However, the light chopper is not operated as such; in this setup, it serves as a holder for the fiber bundle. The chopper blade is carefully adjusted by hand so that the light beam emerges unobstructed.

ductive mode. The resistance  $R$  is set to a value that ensures a good signal is still present at the maximum distance and that no clipping occurs at the minimum distance. For every centimeter or 5-centimeter distance, the photovoltage  $U_{PH}$  is measured and recorded in a table along with the gain  $N$  and the resistance  $R$ . Using these values, a graph of the photovoltage  $U_{PH}$  as a function of distance is plotted.

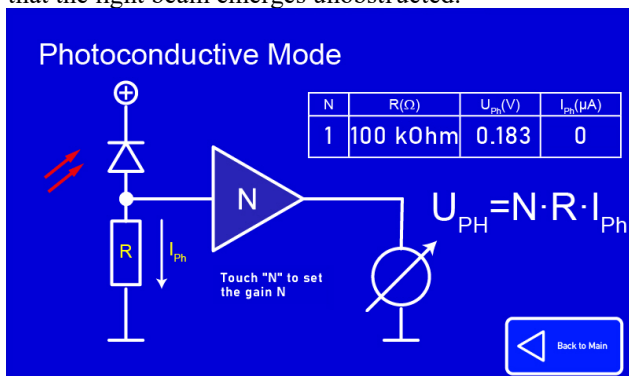


Fig. 30: Use the photoconductive mode

For this measurement, we use the Si detector in photocon-

If an oscilloscope is available, the measurements can be performed using a rotating chopper plate. To do this, connect the PD-OUT output to the oscilloscope. The amplitude of the AC signal is then read as the value for  $U_{PH}$ . This method has the advantage of largely eliminating ambient light.

## 4.2 Photodetector

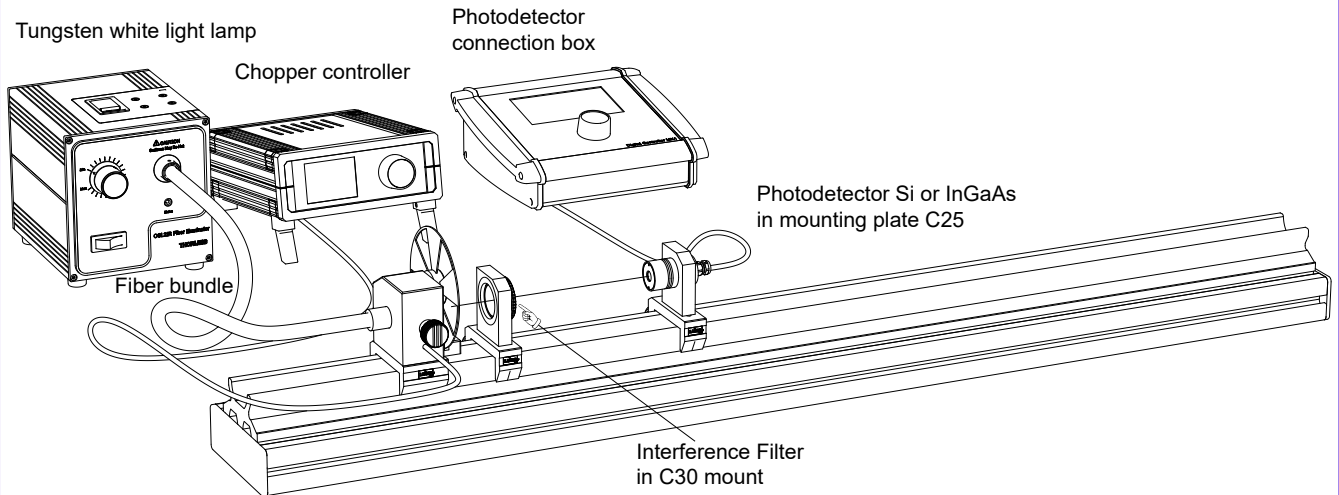


Fig. 31: Experimental setup for the spectral characterization of Si and InGaAs photodetectors.

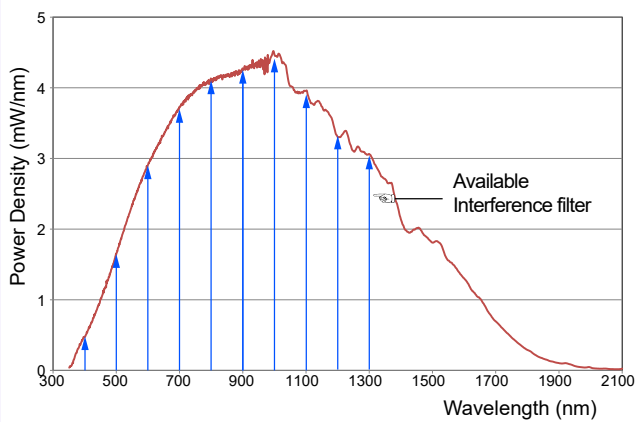


Fig. 32: Calibration curve for the light intensity of the individual bandpass filters

Once the relative output power versus the wavelength has been determined, different measurement tasks can be performed. One example is the determination of the transmission curve of the filter KG5 and RG100. Another example is the determination of the important spectral sensitivity of semiconductor photodetectors.

For spectrally resolved measurements, we have 10 bandpass filters ranging from 400 to 1300 nm at our disposal. Each filter has a transmittance of 90% at its respective wavelength. From the spectral emission curve of the white light lamp, we determine the intensity  $I_0(\lambda)$  and normalize it to 1. Using the photodetector, we measure the photovoltage  $U_{PH}$ , which is normalized to  $I_0(\lambda)$ .

$$S(\lambda) = \frac{U_{PH}}{0.9 \cdot I_0(\lambda)}$$

## 4.3 Filter Characteristic

Now that the spectral sensitivity of the photodiodes used is known, the spectral transmittance of the KG5 and RG1000 filters can be determined.

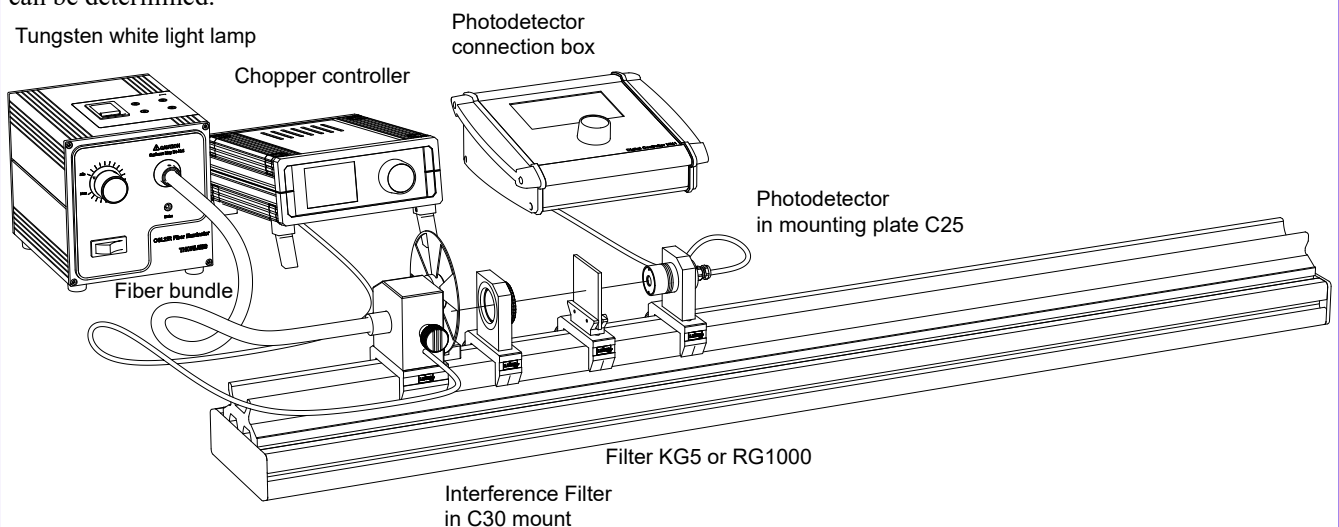


Fig. 33: Setup for Determining the Spectral Transmittance of Filters

The KG5 or RG1000 filter to be measured is placed between the respective bandpass filter and the photodetector. The filter holder is moved close to the photodetector (closer than shown in the schematic diagram). For a specific bandpass filter (wavelength), we measure the photovoltage  $U_{PH}$  once

with and once without the KG5 or RG1000 filter.

$$T(\lambda) = \frac{U_{PH}}{U_{PH_0}}$$

The spectral transmittance  $T(\lambda)$  is the ratio of the photovoltage  $U_{PH}$  with a filter to that without a filter

## 4.4 Photodetector Dynamic Behavior

This experimental setup can be used to determine the dynamic behavior of the photodetector. However, an oscilloscope is required for this.

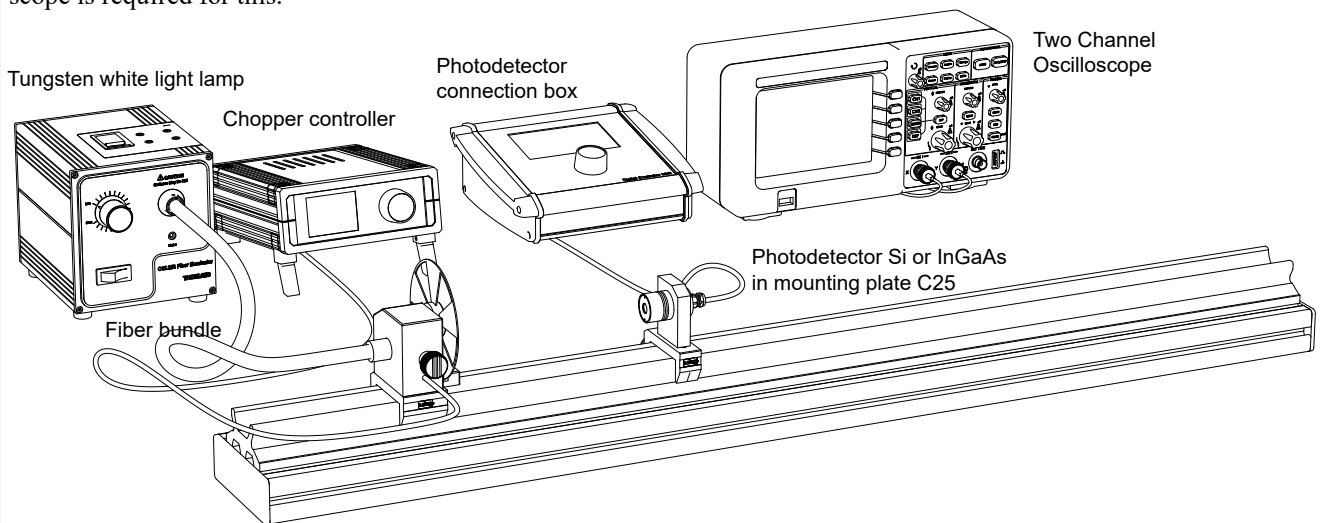


Fig. 34: Experimental Setup for Determining the Dynamic Behavior of a Photodetector

One of the two photodetectors is placed on the rail. The distance is chosen so that a good signal can be observed even with small resistances  $R$ . The PD-OUT output of the photodetector connection box is connected to one channel of the oscilloscope. The chopper reference signal is connected to the second channel of the oscilloscope and also serves as a trigger signal.

= 1 kOhm. The rotational speed of the chopper can be determined from the displayed frequency, taking into account that the chopper blade has 4 segments.

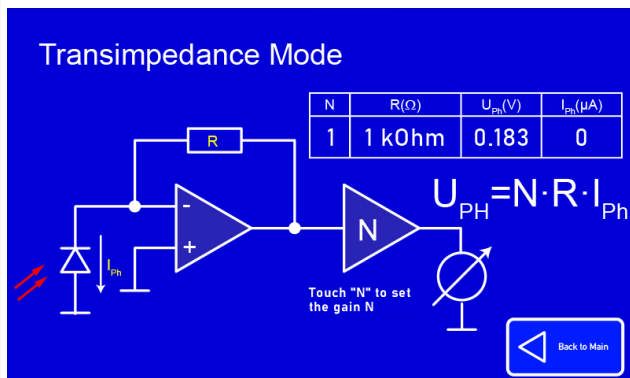


Fig. 35: Here, too, we use transimpedance mode

The yellow signal is the  $U_{PH}$  and the blue one is the chopper reference signal.

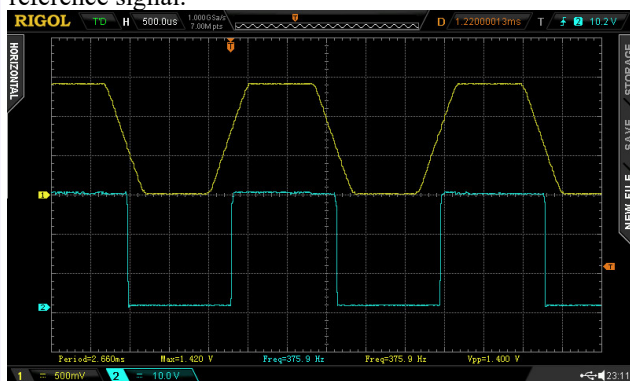


Fig. 36: Resistor value is 1K

We select different values for the resistor  $R$  (1 k and 20 k) and evaluate the signal curve of the photovoltage. Due to the geometry of the chopper blade, the actual time curve has a trapezoidal shape, which is also reflected in the value of  $R$

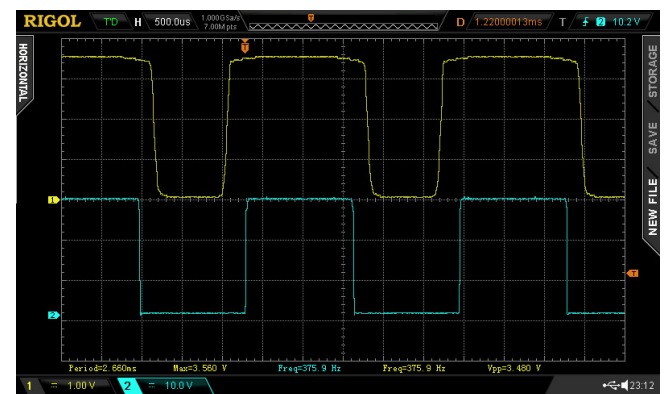


Fig. 37: Resistor value is 20K

With  $R = 20$  kOhm, the amplitude is naturally greater, but the waveform is severely distorted.

These measurements reveal a fundamental behavior of photodiodes that stems from the capacitance of the PN junction. Together with the resistance  $R$ , this forms an RC circuit that determines the frequency response of the photo signal.