T 7.2.6.2

Data Transmission with Optical Fibers 564 492

Technology

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Data Transmission with Optical Fibers

Version: 24BB07PME14W10

564 492

Instructions

EMC

The sensitive electronics of the equipment that is used for experimentation in this manual can be affected by ESD (electrostatic discharge). Therefore, static electricity must be avoided or eliminated by discharge. If necessary, move the experiment set-up to a desk, which is less sensitive to interference.

Experiments

This manual might contain additional experiments with devices which are not included in the scope of delivery. In this case only those experiments can be performed, for which LD delivered the required material. Thus customers are not entitled to claim for compensation such as free-of-charge deliveries of supplementary apparatus. Additional experiments deviating from the procedures described herein are possible, if carried out by qualified personnel taking into consideration prevailing security standards. The sample solutions given in the results are only approximate. Actual results can differ in principle for the following reasons from the figures given here:

- Setting of the operating points (potentiometers, encoders)
- Component and measurement tolerances
- Fluctuations in the supply voltages etc.

All measurement results were recorded with the equipment from the material list. Because the Sensor-CASSY and the software CASSY Lab are very versatile measurement tools, they are preferred for experimentation. DC-power-supplies function generators and measurement instruments can be replaced by substitutes, as long as their electrical data are at least equivalent to the original instruments.

Manuals

Instruction sheets or additional information (software) of third-party devices and must be read prior to the tests.

Further claims from this manual are excluded!

Equipment overview

Qty.	Cat.-no.	Designation
1	736 061	PAM Modulator
1	736 071	PAM Demodulator
1	736 101	PCM Modulator
1	736 111	PCM Demodulator
1	736 401	Fiber Optic Adapter
1	736 415	Fiber Micropositioner
1	736 425	Set of FSMA Optical Fibers
		Accessories
1	726 09	Panel Frame –T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
2	726 962	Function Generator 200 kHz
4	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
1	500 592	Set of 10 Safety Bridging Plugs with Tap, black
2	500 614	Safety Connection Lead 25 cm, black
4	500 644	Safety Connection Lead 100 cm, black
		Measuring instrument
1	524 013S	Sensor-CASSY 2 - Starter
		Additional accessories
1	736 429	Fiber optic microscope
1	524 0512	Optical Power Sensor S
1	736 416	Mode Scrambler

Contents

Training objectives

- Determining characteristics of LEDs and photodiodes.
- Dependency of the wavelength λ of the emitted light on the threshold voltage U_S.
- Current / power characteristics of the LEDs.
- Features of photodiode and the transimpedance amplifier.
- Determining the optical power of LEDs.
- Fiber attenuation as a function of the fiber length.
- Fiber attenuation for various light wavelengths.
- Investigating analog optical transmission systems.
- Setting up digital optical transmission systems.
- Determining the coupling losses in the case of misaligned fiber connections.
- Determining the numerical aperture (NA).

Optical transmission technology

In 1792 the French engineer Claude Chappe invented the optical telegraph. His devices consisted of tower-type or platform constructions, which transmitted messages by altering the position of their moveable arms. His apparatuses called semaphores were in operation until the mid-19th century. They were capable of transmitting messages from Lille to Paris inside of two minutes. Message transmission via smoke signals and light signals were based on the same principle. The disadvantages of these methods are evident: information could easily be intercepted by unwanted receivers, and transmission was distorted during poor weather or at night. However, until far into the industrial age there was no better possibility for rapidly transmitting information to remote corners of the planet. Only after the discovery of the electric telegraph was it possible to solve this problem. Whereas at the beginning of the 19th century the transmission of one letter (1 Byte) took six minutes to travel from Paris to Strasbourg, corresponding to 0.02 bps. Gauß and Weber were able to transmit seven letters per minute in 1835 in Göttingen using their electric telegraphs and only 80 years later fast-operating systems were transmitting 1000 letters per minute. We do not wish to give a detailed description of this development but prefer rather to make a historical jump to the recent past. C. Kao (1963) and M. Börner (1964) are now recognized as the inventors of optical transmission of electromagnetic waves in the near-infrared range using glass fibers. Naturally, at that time the attenuation coefficient of glass was still over 1000 dB/km, so that any practical application was still unthinkable. The breakthrough came in 1970, when the company Corning Glass Works was able to manufacture optical fibers with an attenuation of 20 dB/km. In fact by the beginning of the seventies all of the basic components necessary for optical communications – light source, optical fibers and photodetectors – had been developed, ushering in the process of optimization which has continued to this day.

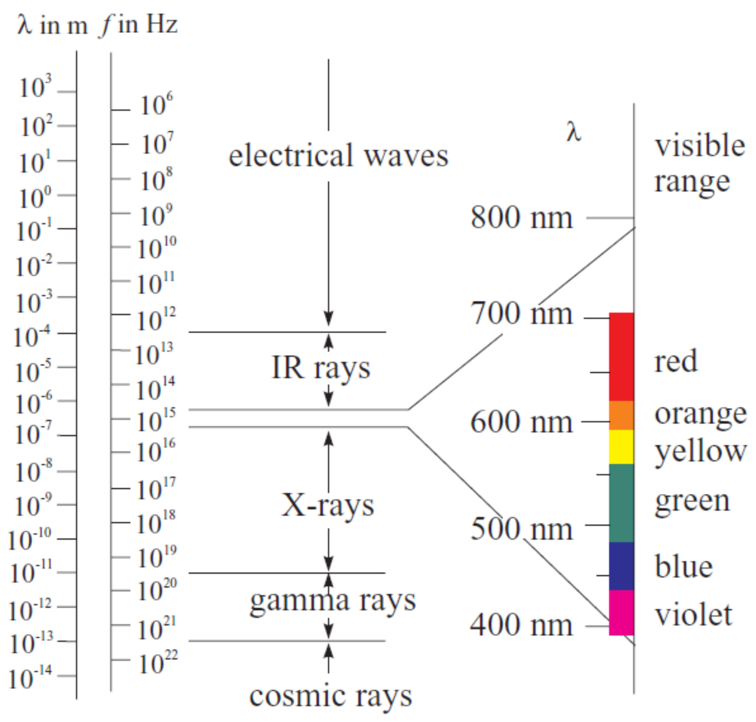


Fig. 1: The electromagnetic spectrum

Physical principles

The electromagnetic spectrum, light

For the transmission of messages the propagation of electromagnetic waves in a transmission medium is of fundamental importance. This does not necessarily have to be a metal conductor, waves can also propagate in a vacuum or in a dielectric material. The **spectrum** of electromagnetic waves reaches from the long radio waves up to shortwave cosmic rays. For optical communications technology only a very small range is suitable, namely infrared (IR) and visible (VIS), as well as the ultraviolet (UV) component of the electromagnetic spectrum. Here, visible light takes up only the narrow range of 380 nm (violet) up to 780 nm (red). Bordering this range toward the smaller wavelengths are the ultraviolet rays while the IR rays are located at larger wavelengths. Light in the narrow sense of the word refers to the electromagnetic waves in the visible range, although this definition often includes the IR and UV range. The following relationship (1) exists between the wavelength λ and the frequency *f*:

$$\lambda = \frac{c}{f} \tag{1}$$

Where *c* stands for: 3 10^8 m/s, the velocity of light in free space. The range from 500 nm up to 1500 nm is particularly well-suited for optical transmission.

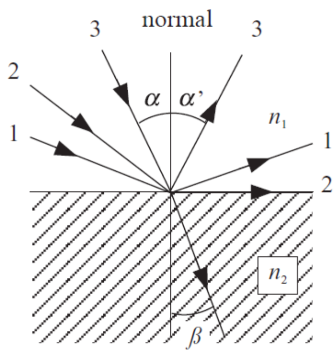


Fig. 2: Reflection and refraction

Beam optics, design of an optical fiber

Light propagation in a multimode optical fiber can be explained using the laws of geometrical optics. "Light beams" are theoretical constructs. They represent the ideal form of cones of light with small aperture angles, propagating in straight lines. They can be guided or deflected into other directions using mirrors, prisms or lenses. The process of guiding light in an optical fiber is based on the laws of refraction and reflection. As a rule both processes occur when a ray of light incidents a dielectric surface. If a ray of light strikes the surface of two different substances with different refractive indexes *n*, then the following holds true according to the law of reflection:

$$\alpha = \alpha' \tag{2}$$

The angle of incidence α and angle of reflection α′ are in the same plane. According to Snell's law of refraction the non-reflected component of the light beam proceeds on its path in the second medium with an altered propagation direction. The law of refraction is stated as follows:

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2} \qquad (3)$$

The ratio of light velocity c_0 in a vacuum to the velocity of light c of the medium is called the refractive index n. It is a material constant and indicates by how much the light velocity in a medium is smaller than in a vacuum.

$$c = \frac{c_0}{n} \qquad (4)$$

Using the equation (4) we obtain:

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1} \qquad (5)$$

When the angle of incidence α is increased, the angle of refraction ß reaches the value ß = 90° during the transition from an optically denser medium with refractive index n_1 to an optically less dense medium with refractive index n_2 (Attention: Fig. 2 presupposes that $n_1 < n_2$!). In the case of two opaque media the one designated optically denser is the one in which the light velocity is lower. The corresponding angle of incidence α_C is called the critical angle:

$$\sin\alpha_G = \frac{n_2}{n_1} \qquad (6)$$

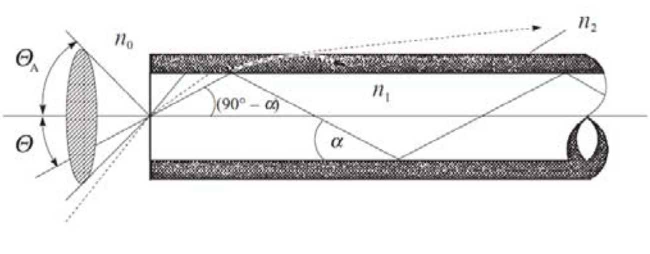


Fig. 3: Light guided through a fiber optic fiber

Thus, if the angle of incidence surpasses the critical angle α_C, no refraction can occur and the light rays are totally reflected at the surface. This phenomenon is called total reflection. This can only take place during the transition from an optically denser medium to an optically less dense one and is exploited as the guiding mechanism in optical fibers (multimode fibers). For this reason the optical wave guide consists of a cylindrical core and a concentric cladding surrounding it (see Fig. 3). Here the refractive index n_1 in the core glass is somewhat larger than that of the refractive index n_2 in the glass cladding. From (6) it follows that all of the light rays which do not deviate more than (90° – α_C) from the axial direction of the optical fiber are guided inside the glass core. In order to launch or couple a light beam into the glass core from an external source (air with refractive index n_0 = 1), the following holds true for the coupling angle Θ, which confines the light beam to the direction of the optical fiber axis (see Fig. 3), in accordance with (7):

$$\frac{\sin\Theta}{\sin(90° - \alpha)} = \frac{n_1}{n_0} \qquad (7)$$

From this it follows with $n_0 = 1$ that

$$\sin\Theta = n_1 \cdot \cos\alpha = n_1 \cdot \sqrt{\left(1 - \sin^2\alpha\right)} \qquad (8)$$

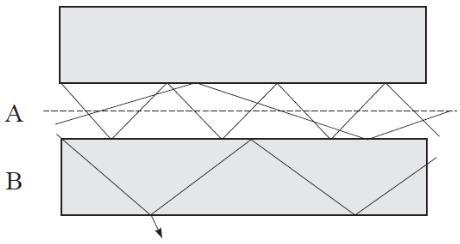


Fig. 4: Modal dispersion in a step-index fiber
(A) Core modes
(B) Cladding modes

The corresponding, largest feasible coupling angle Θ_A is called the acceptance angle of the fiber optic fiber and is only dependent on the two refraction indexes n_1 and n_2. The sine of the acceptance angle is called the numerical aperture NA of the optical fiber:

$$NA = \sin\Theta_A = \sqrt{n_1^2 - n_2^2} \qquad (9)$$

This variable is extremely important for coupling light into a fiber optic fiber. The greater the numerical aperture of an optical fiber, the more light can be coupled. As a disadvantage a great NA also introduces more propagation time differences between higher order modes.

Fiber optic profiles

If we consider the refractive index *n* of a fiber optic fiber as a function of the radius *r* of the core material, this relationship is referred to as an index profile. In practice two refractive index profiles have prevailed:

- Step-index profile
- Graded-index profile

The step-index profile is characterized by a constant refractive index n_1 within the core and a sharp drop to n_2 ($n_1 > n_2$) at the surface between the core and cladding. Fig. 4 shows that the rays guided in a flatter fashion travel a shorter distance than the ones travelling at a steep angle because the latter types are reflected more frequently. These are referred to as modes of higher order (multiple zigzag course) and accordingly modes of a lower order (few reflections). Modes are a complex mathematical and physical concept describing possible propagation paths in a fiber optic fiber. The existence of modes of various orders leads to complications in signal transmission as the following consideration demonstrates. A light pulse of short duration is guided over many different paths, (higher modes with various propagation times). Out of brief, sharply time limited input pulses, a severely dispersed pulse (mode dispersion) appears at the output, which is the sum of all signals reaching the fiber's end one after the other. Thus the stepped optical fiber is not suited for the transmission of broader bandwidths.

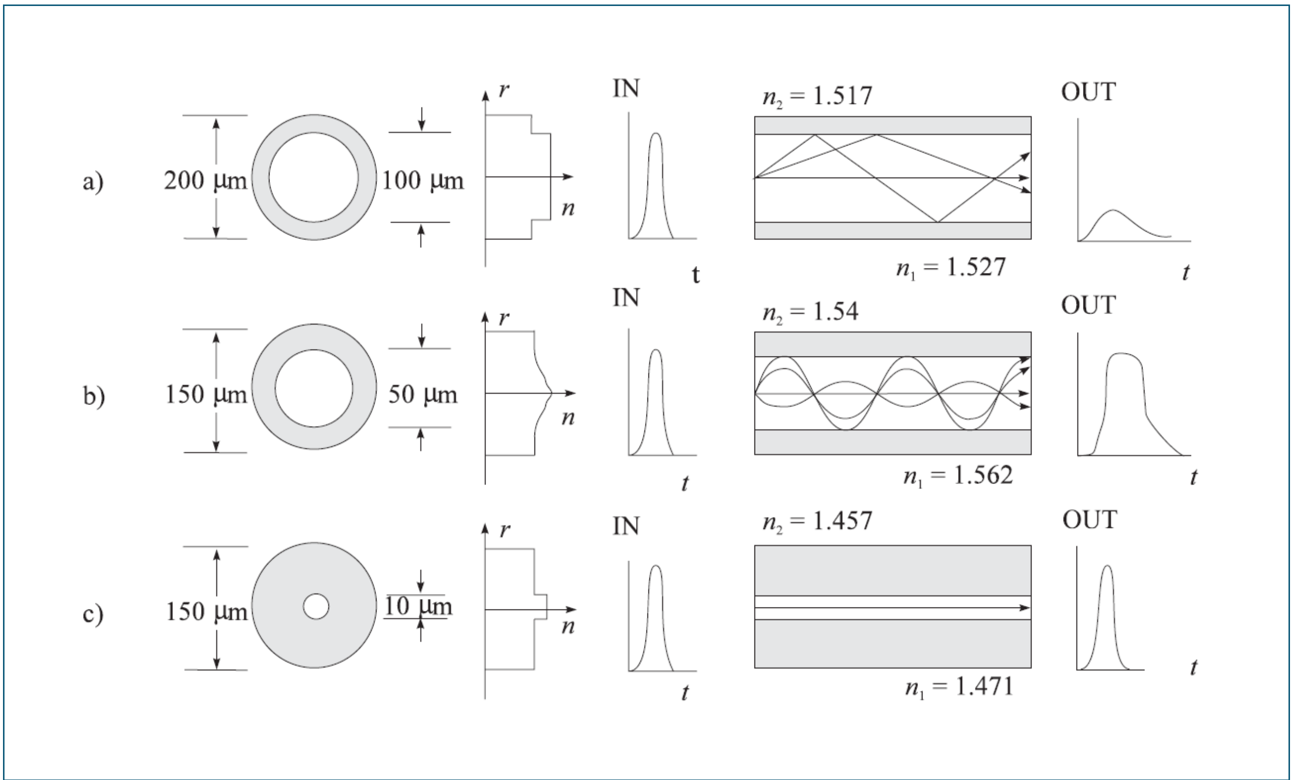


Fig. 5: Overview of common types of fiber optic fibers
(a) Multimode step-index
(b) Multimode graded-index
(c) Monomode fibers

The graded-index profile provides assistance here. In contrast to the step-index profile the light rays in a graded optical fiber do not propagate in zigzag fashion. The refraction index profile of a graded optical fiber changes continuously over the radius of the fiber. The guiding mechanism of the graded optical fiber is no longer based on total reflection but on refraction. Frequently a parabolic profile is used. Due to the continuously changing refractive index *n(r)* in the glass core, the rays are constantly subjected to refraction. The propagation direction is constantly changing, running in wavelike paths along the axis of the fiber. In the process the steep rays oscillating around the axis always have farther to travel than the light ray travelling along the axis. However, due to the ever-lower refractive index outside the axis of the fiber these rays travel at correspondingly faster speed, through which the longer distance is made up for in time (see (4). As a result, the differences in propagation time for the individual rays disappear almost completely. Modal dispersion is only slight. In order to achieve maximum transmission performance, a special kind of step-index fiber is used; the single mode fiber (monomode fiber). The fiber radius must be in the range of 2…10 µm. Only one single mode can propagate along the core thus eliminating the possibility of any propagation time difference. (No modal dispersion). Fig. T5 provides an overview concerning the dimensions, refractive index profiles and some additional characteristic variables.

Fiber production, material selection

For various reasons, the materials plastic and silica glass have gradually become predominant for the production of fiber optic fibers.

PMMA fibers

Plastic fibers are commonly used in industry. The most common fiber type consists of an approx. 970 µm thick core of polymethylmethacrylate (PMMA) and an approx. 15 µm thick cladding made of silicone or Teflon. PMMA is primarily used to manufacture step-index fibers. They are easy to handle, robust and are well suited for employment in industrial application for short and medium-length links (up to approx. 100 m). Fig. T6 shows the schematic design of a PMMA fiber. The NA amounts to 0.47 which corresponds to a half-aperture angle of 28°. For high speed transmission links (e.g. cable networks and telecommunication networks operated by telephone and communications companies throughout the world) monomode fibers are needed. These are manufactured out of silica glass like step-index fibers. The advantage of silica fibers is a considerably lower attenuation level.

HCS fibers

HCS is the abbreviation for **H**ard **C**lad **S**ilica. This type of fiber constitutes a further development of the traditional PCS fiber (**P**lastic **C**lad **S**ilica). As an alternative to optical fibers in which both optical layers consist of glass, the cladding of PCS fibers is made of a transparent plastic. The plastic cladding demonstrates a considerably smaller refractive index n_2 than the core glass n_1. According to (9) this results in a high numerical aperture. Suprasil or spectrasil are used as high purity types of core glass. The typical design of an HCS fiber is shown in Fig. 6. HCS fibers have a step-index profile. The fiber core consists of high purity silica glass. A hard polymer is applied directly to the surface of the silica glass core as optical cladding. The fixed bonding of the plastic cladding to the core material constitutes the main difference to PCS fibers. Special connectors can be crimped directly to the plastic cladding of the HCS fibers. The core does not protrude out of the cladding like in PCS fibers.

Due to the material properties, PCS fibers have the following interesting features:

- PCS fibers are easy to manufacture. They only need a fiber drawing tool for the preform. The jacket is applied by immersion in liquid plastic.
- The high attenuation of the jacket material contributes only slightly to the total attenuation, because the light is primarily guided in the low attenuation core material.

- The attenuation response is good when exposed to radioactive radiation.
- The temperature dependency of the attenuation is relatively high due to the varying temperature responses of the core / cladding materials (due to the dependency of density and refractive index on the temperature).
- With increasing fiber lengths the numerical aperture decreases due to the increasing attenuation of the higher-order modes penetrating into the cladding.
- Due to the large numerical aperture the coupling of PCS-fibers to inexpensive LEDs is easy to realize.
- The wavelength dependent attenuation characteristic of PCS-fibers deviates considerably from that of glass / glass fibers, see Fig. 8.

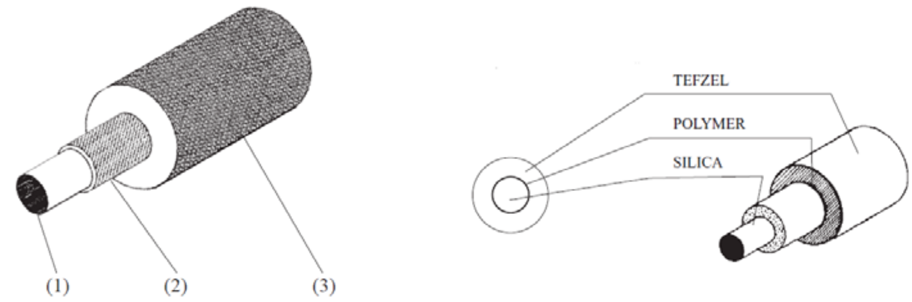


Fig. 6: Design of a PMMA fiber und a HCS (PCS) fiber
(1) Core ø= 970 µm. n_1 = 1.492
(2) Optic cladding thickness. Thickness: 15 µm, n_2 =1.417
(3) Protective jacket ø = 2.2 mm(buffer)

Attenuation mechanisms on optical fibers

Any form of energy transmission involves power losses. In communications this is referred to as attenuation. Important examples of this in optical communications technology are:

- Coupling attenuation of the connector
- Material attenuation of the fiber optic fiber

The attenuation of the fiber optic fiber is dependent on the wavelength, as shown in Fig. 7. In contrast, the attenuation of the connectors is to a great extent independent of the wavelength. The coupling attenuation mainly depends on the beam angle of the light source and the aperture angle or numerical aperture of the optical fiber. During the transition from connector to connector the light is refracted while passing through the air. As a result a portion of this light no longer arrives at the aperture angle on the front side of the fiber optic fiber and is thus lost for signal transmission.

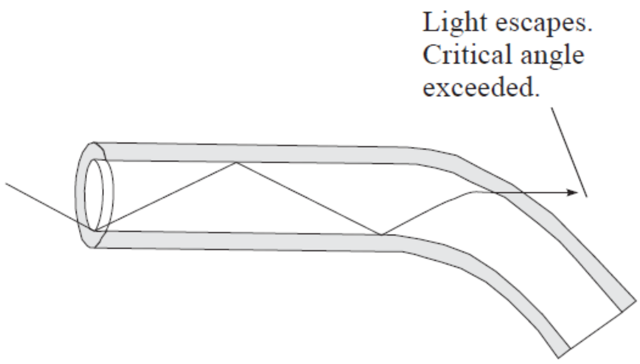


Fig. 7: Transition from guided to unguided modes

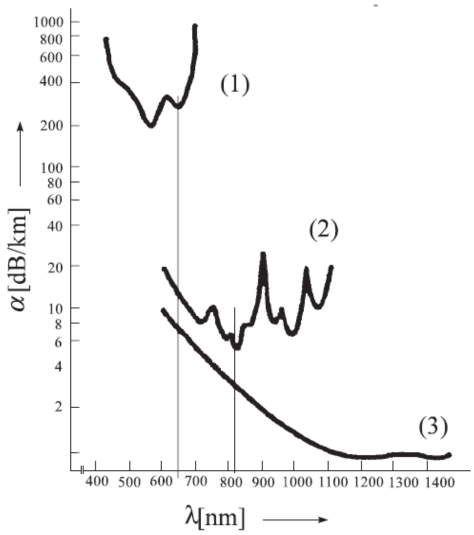


Fig. 7: Fiber optic attenuation distribution
(1) All Plastic Fiber e.g. PMMA
(2) Plastic Cladding Fiber e.g. HCS
(3) Glass

Material attenuation of the fiber optic fiber is caused by:

- Light scattering
- Light absorption
- Beam losses related to the guiding properties of the fiber.

Causes for linear scattering (Rayleigh scattering) are statistical fluctuations in the refractive index. These result from random molecular structures in the fiber material used. The refractive index varies within ranges which are small in comparison with the wavelengths of light. In the case of absorption, we are primarily dealing with the conversion of beam energy into heat when impinging on impurities (foreign atoms or molecules). The severity of the effect depends on the wavelength and spans the entire range, from ultraviolet to infrared. One peculiarity is an additional absorption, which occurs in particular in ultraviolet and infrared ranges. The reason for this is the molecular structure of the fiber material. In addition to the scattering and absorption there also exists beam losses through conversion from guided modes to unguided modes. Fluctuations in diameter or concentrations etc. are responsible for this. Furthermore, there are modes in which energy flows from the core into the cladding: Leaky modes are produced. The tendency to leaky mode formation increases, when the fiber becomes bent (see. Fig. 6). However, due to the relatively high attenuation in the cladding material mantle modes are incapable of propagation even without a bent optical fiber. Ranges in which the attenuation assumes minimum values are referred to as optical windows.

In conjunction with the corresponding emitter elements the range around 660 nm is used in plastic optical fibers and the range around 850 nm (1st window) and around 1300 nm (2nd window) for glass optical fibers.

Fiber connectors

Temporary connectors are extremely important in commercial optical communications technology. They permit system components to be interchanged and networks to be extended. Important features of an optical connector are:

- Operating life
- Contact play
- Insertion loss
- Operating temperature
- Protection against displacement (important for polarization-sensitive equipment)
- Material selection

Fig. 9 shows a typical optical fiber connection with connectors and coupling. Fig. 8 depicts the set up of an FSMA connector.

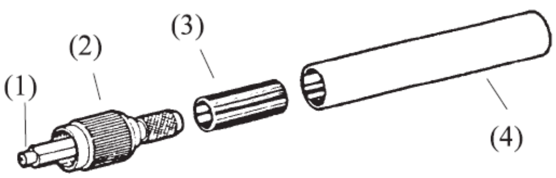


Fig. 8: Design of an FSMA connector
(1) Connector sleeve
(2) Housing
(3) Crimp sleeve
(4) Anti-bend socket

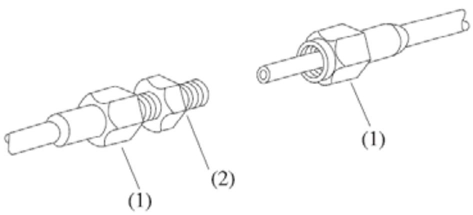


Fig. 9: Fiber optic link using connectors
(1) FSMA connector
(2) FSMA coupling

Important aspects in the construction of plug connectors came about because of the need for the best possible positioning of the joint surfaces being coupled. This results in the demands to minimize the following:

- lateral offset
- axial separation
- angular offset

An inexpensive connector used commercially world-wide corresponds to the FSMA standard. The design of this connector was based on the SMA standard frequently used in RF technology. In order to characterize this connector as a component in optical transmission systems, an F has been added to denote fiber. Today connectors designed in accordance with the FSMA standard are the components of choice in data technology for point-to-point connections and in applications with large core fibers in medical technology. FSMA connectors are air-gap connectors, i.e. the end faces of the fibers lying opposite to each other do not touch. The connector sleeve has a diameter of 3.175 mm and cylinder-shaped in type 905 and protrudes out in type 906. The thread is equipped with a union nut. Depending on the model, FSMA connectors are not defined with respect to their angular position and hence are only suitable for non-polarization sensitive connections. Tightening the union nut does take some time. There are also bayonet connectors for quick connections and also provide protection against angular displacement.

Light sources

In terms of light sources used in optical communications technology we are dealing primarily with LEDs and solid-state lasers (LD). Taken from the electrical point-of-view these semiconductor light sources are considered pn-diodes, which are operated in the forward direction. In semiconductor technology electro-optic converters made of III-IV-V- materials and their combinations, e.g. InGaAsP / InP have proven to be very suitable. Here we are dealing with chemical elements of the third to fifth groups of the periodic table. From a physical point-of-view the effect of spontaneous recombination is exploited. In the process electron hole-pairs combine without external influence, while their energy is released in light photons. The frequency of these photons is determined by the band gap E_G between the conducting band and the valence band of the semiconductor material used. The following applies:

$$E_G = h \cdot \nu \tag{10}$$

Where:

h Planck's constant (6.6256 10^{-34} Js)
E_G Energy difference

By doping with foreign atoms (aluminum, phosphorous, indium) the crystal structure and thus also the band gap are constantly changing. In LEDs this leads to different emission wavelengths (colors). The LED supplies an incoherent beam, which either exits perpendicularly to the pn-layer (surface emitter) or at an open lateral edge (edge emitter) emitting a diffuse light cone into the entire neighboring half-space. The current/voltage characteristic essentially shows the same behavior as a normal Si-diode or Ge-diode. When an external voltage is applied in the forward direction the electrical field generated at the pn-junction does not initially suffice to evoke a charge flow. Only after the so-called threshold voltage U_S has been exceeded, does the current increase radically. The diode characteristic in the flow direction ($U_F > 0$) is described by the differential resistance r_F:

$$r_F = \frac{\Delta U_F}{\Delta I_F} \quad (11)$$

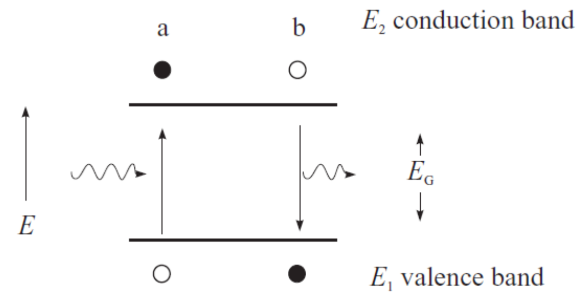


Fig. 10: The band model of the semiconductors

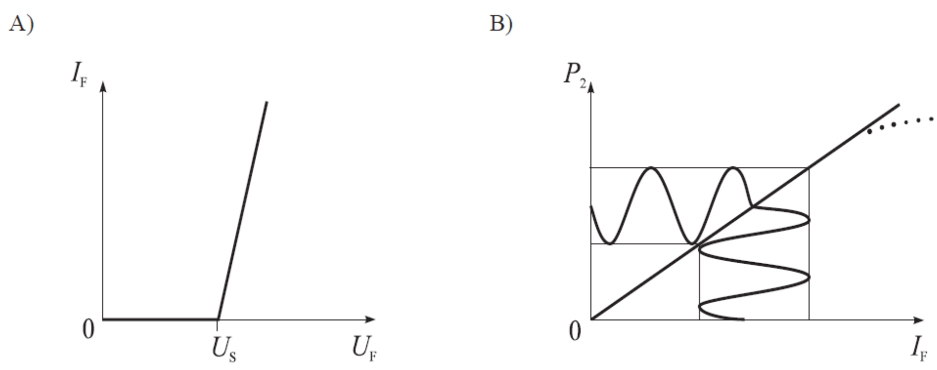


Fig. 11: LED characteristics
(A) Idealized current/voltage characteristic
(B) Optical power P_2 of an Led as a function of the forward current I_F

For $U_F < U_S$ the differential resistance assumes a large value and for $U_F > U_S$, a small value. The threshold value can be determined approximately by setting the tangent against the steep side of the characteristic and prolonging the line to the voltage axis. The actual non-linear, steep range of the curve can be described by the following function:

$$I = I_S \cdot (e^{\frac{U_F}{U_T}} - 1) \quad (12)$$

I_S is the so-called saturation or reverse current of the diode and U_T the temperature voltage, which can be assumed to be constant. Because of their low cut-off frequency and output power – compared to laser diodes – LEDs are only used in systems with short transmission links and low data bit rates. If the polarity of the voltage being applied to the diode is mistakenly interchanged, then a charge-carrier-free space is produced inside the pn-structure. Current can no longer flow, the diode blocks. Only when the applied reverse voltage exceeds its critical value does the excessive field strength destroy the pn-junction. In addition to the current/voltage characteristic the representation of the generated optical power P_2 as a function of the forward current I_F is also of interest in LEDs (PI characteristic). Typical characteristics are shown in Fig. 11. A saturation effect can be observed in the current/ power characteristic (dots). The reason for this is the power dissipation arising at higher currents. As the diode heats up, the rise in power is reduced. In order to keep the heating temperature as low as possible, efforts have to be made to ensure good thermal dissipation. The efficiency of the LED is relatively low, as the generated beam is partially re-absorbed or does not even escape the crystal due to total reflection. One advantage for analog modulation is the linear power-current-characteristic (PI), which spans a wide range. This prevents the generation of harmonics. Therefore, an LED is particularly well-suited for use in analog applications with their attendant demands on linearity.

Operating of LEDs

The LEDs used in optical transmission technology have low-pass characteristics. Here the diodes emitting in the visible spectral range demonstrate a 3 dB-cut-off frequency of rarely more than 8...10 MHz, see Fig. 12.

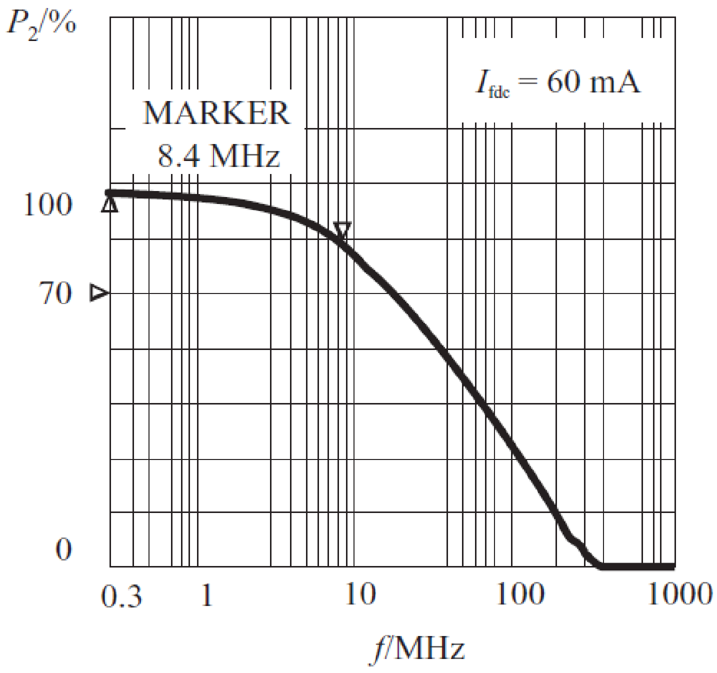


Fig. 12: The low signal frequency response of LEDs. P_2/%: relative optical power

The behavior described by Fig. 12 does not explain the abrupt step response of the LEDs. This response particularly important in digital data transmission is caused by non-linear effects within the pn-junction. When the LED is switched off, the dynamic impedance of the pn-junction increases abruptly. As a consequence the charge carriers stored in the depletion layer are momentarily blocked. The charge flow out of the LED caused purely by diffusion can only proceed very slowly. This leads to a gradual reduction in light transmission. The current-time characteristic of an LED is presented in Fig. 13.

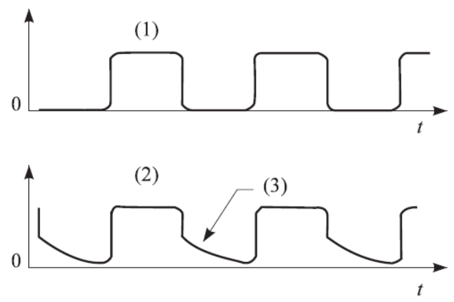


Fig. 13: Abrupt step response of the LED
(1) Input signal at LED driver
(2) Characteristic of the LED current and the optical power with fading tail (3)

At switch off the diode current undergoes an exponential decay which is clearly discernible. This leads to a correspondingly distorted receiving signal in a receiver connected downstream for the very reason that the LED only sets its light emission with time delay. As a consequence intercharacter distortions can arise which limits the maximum bit rate which can be transmitted. When a bias current is used, the ratio improves markedly. The LED is no longer switched off completely but merely switches between two current values in the forward direction. Furthermore an effective derivative-action element can be achieved from the low-pass characteristic according to Fig. 13, which accelerates the charge carriers flow out of the depletion layer. The negative current pulses cause a rapid discharge of the depletion layer and the optical decay time is reduced. The bias current also improves the switching times between switch-on and switch-off. The Fig. 14 shows the voltage characteristic at the input of the LED driver for the non-accelerated normal mode and the differentiated peaked mode supplied with bias current.

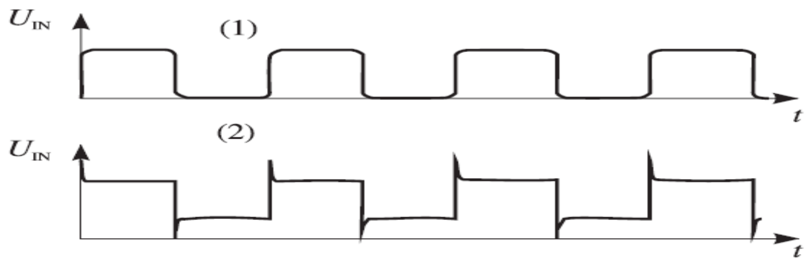


Fig. 14: Abrupt step response of the LED
(1) Normal mode
(2) Peaked mode

Detectors

The opto-electrical conversion brought about by the absorption of the light ray takes place in the photodiode. In this process an arriving, photon with a higher energy level than that of the band gap *E*G, transfers its energy to an electron of the valence band, which causes this electron to be bumped into the higher energy conduction band (see Fig. T10). The photon vanishes in the process and leaves behind a free space in the valence band (also called a hole), which is used to transport current. Primarily silicone and germanium or the III-IV-V- compounds are used to manufacture receiving elements. Silicon is particularly well suited for the range below 1000 nm. Germanium is better for greater wavelengths. For practical applications the spectral sensitivity *SE* is important. This indicates which current I_p is obtained at the photodiode for a specific, incident light power P_2. Typical values for silicon diodes for a wavelength of 850 nm are at about SE = 0.5 A/W. The Fig. T10 demonstrates the relative sensitivity of photodiodes as a function of the wavelengths for various semiconductor elements when compared to the sensitivity of the human eye. In pure semiconductor material without a pn-junction there is the danger that the electron hole pairs generated by photon absorption partially recombine, i.e. are destroyed again and thus are unable to contribute any longer to the photocurrent. A pn-junction biased in the blocking direction responds better in this respect. Without light incidence only a very slight dark-current flows. Because the absorption of the photons occurs in part outside of the drift area, these kinds of photodiodes are relatively slow. In this respect the use of PIN diodes is more favorable. In this case an intrinsically conductive layer is integrated between the P- and the N-doped areas. In the I-zone, the degree of N-doping is just as large as that of the P-doping.

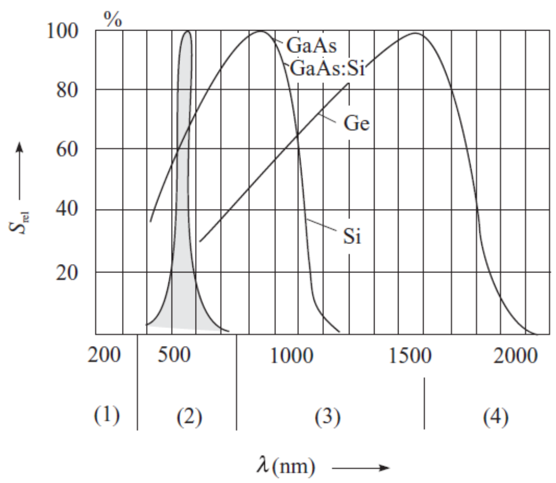


Fig. 15: Relative spectral sensitivity of photo diodes
(1): ultraviolet light
(2): visible light
(3): near infrared
(4): mean infrared
(grey): sensitivity of the human eye

Questions

1. Optical transmission in fiber optic fibers takes place according to which laws?

Light propagation occurs according to the laws of optics. In multimode fibers these are the laws of total reflection and refraction.

2. The laws of beam optics apply under what conditions?

The laws of beam optics apply as long as the wavelength of the light is small with respect to the dimensions of the optical structures. In fiber-optic technology a distinction is made between between two limiting cases:

– The wavelength of light is very much smaller that the core diameter of the optical fiber $\lambda << \Phi$. This applies in all multimode fibers. Then the way the light is propagated can be explained using the laws of beam optics (laws of total reflection, refraction).

– The core diameter of the optical fiber is comparable with the wavelength $\Phi \sim \lambda$. This case arises in monomode fibers. Here light propagation can only be explained using the complicated laws of wave theory.

3. What limits the data transmission rate of LEDs?

The data transmission rate is limited in LEDs by the charge storage in the depletion layer. The finite evacuation time of charge carriers out of the depletion layer determines the bandwidth of an LED.

4. What possibilities exist to increase the data rate?

The transmission rate of LEDs can be increased by operation in “peaked mode”. Here the LED is fed with a bias current. It no longer switches off completely but switches between two finite current values. Furthermore, a differential circuit can be used to counteract the LP-behavior of the LED, in order to improve the LED switching performance (lead compensation).

5. How is the FSMA connector constructed and what kind of features does it have?

The FSMA connector is a so-called air-gap connector. The two optical fibers to be coupled to each other are connected without contact. The FSMA connector consists of connector sleeve, housing with union nut, anti-bend sleeve.

Its insertion loss is specified at up to 2 dB per connector. This is a high value compared to the low attenuation values of high-performance glass fibers. This attenuation corresponds to many km's of glass fibers. For this reason connector couplings are only used, where a releasable connection is required.

Equipment

736 401 Fiber optic adapter

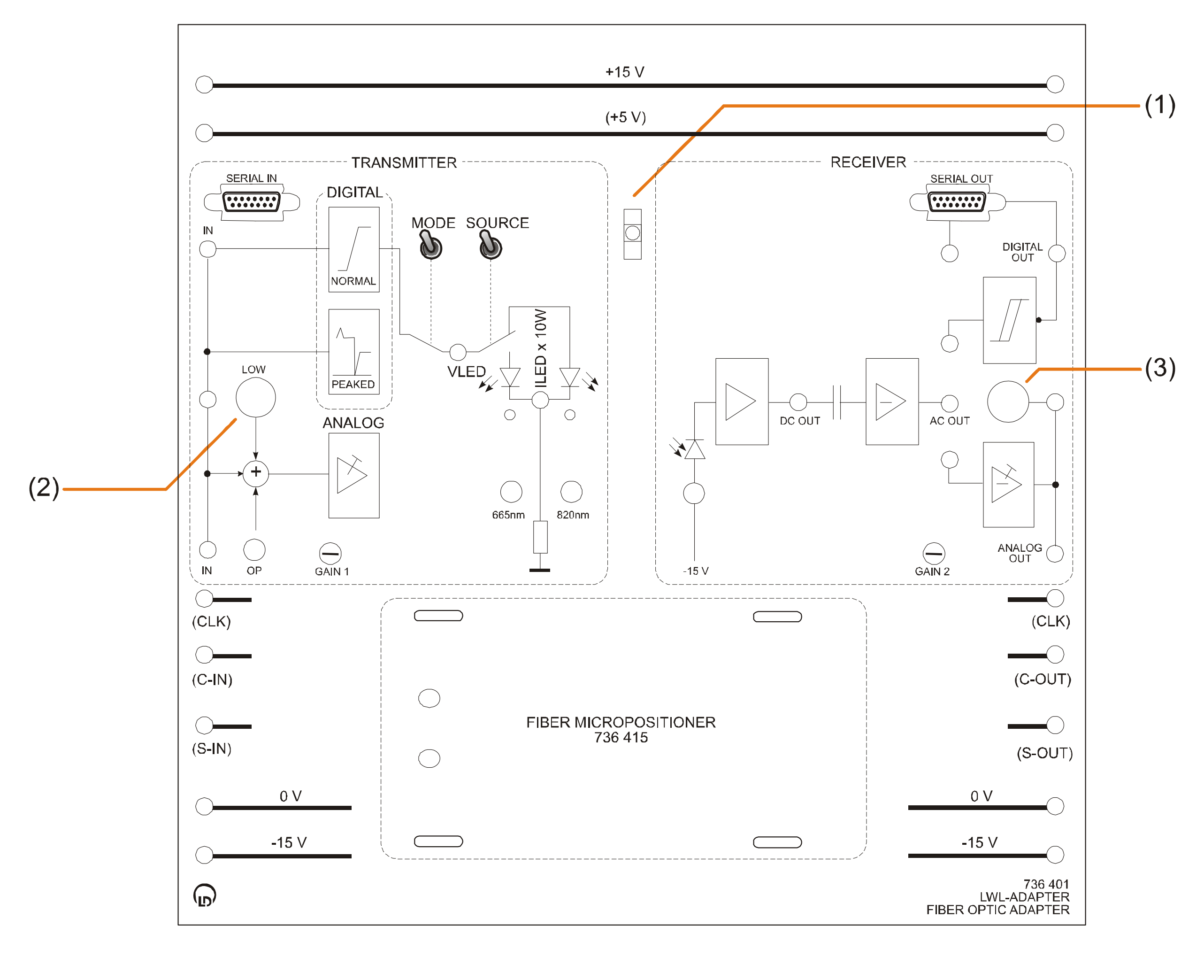


Fig. 16: The Fiber optic adapter 736 401

OP: The operating point controller sets the required DC voltage operating point for analog operation approx. 0…2 V. Also important for recording characteristics (V1)
GAIN 1: Gain matching foe various modulation signals of the LEDs in analog operation
GAIN 2: Gain matching for receiving signals of varying strength in analog operation
(1): Mounting clamp for fiber optic fiber
(2) (3): In broadband analog applications use BNC sockets and cable

The adapter permits the integration of a fiber optic fiber link into the training panel system for transmission technology. Each one contains one complete fiber optic transmitter and receiver, which can be linked up using interchangeable optical fibers. The adapter has two LEDs as well as one PIN photo diode in commercial FSMA design built-in. The LED drivers on the transmitter side can be operated by function generators or modulators of any kind. The fiber micropositioner (736 415), can be attached directly to the fiber optic adapter. This makes it possible to simulate faulty connections or to measure the numerical aperture.

Technical data:

Voltage supply : ±15V DC

Transmitter:

Light sources : One LED each for 665 nm and 820 nm

Operating modes : analog/digital (normal/peaked)

Inputs : BNC/4-mm sockets

Receiver:

Photo receiver : PIN-photo-diode with transimpedance amplifier, ca. 10 MHz bandwidth

Outputs : Comparator and adjustable analog amplifier with BNC/4-mm sockets

Spectral characteristics of the LEDs and the photo diode of the fiber optic adapter see Fig. 17.

Notes

Relationship between the optical power radiated onto the photodiode of the fiber optic adapter and the output voltage at the transimpedance amplifier, i.e. analog out:

- To determine optical power levels or power ratios the photo diode of the fiber optic adapter 736 401 can be used.
- Voltages at AC OUT and Analog OUT are proportional to the optical input power.

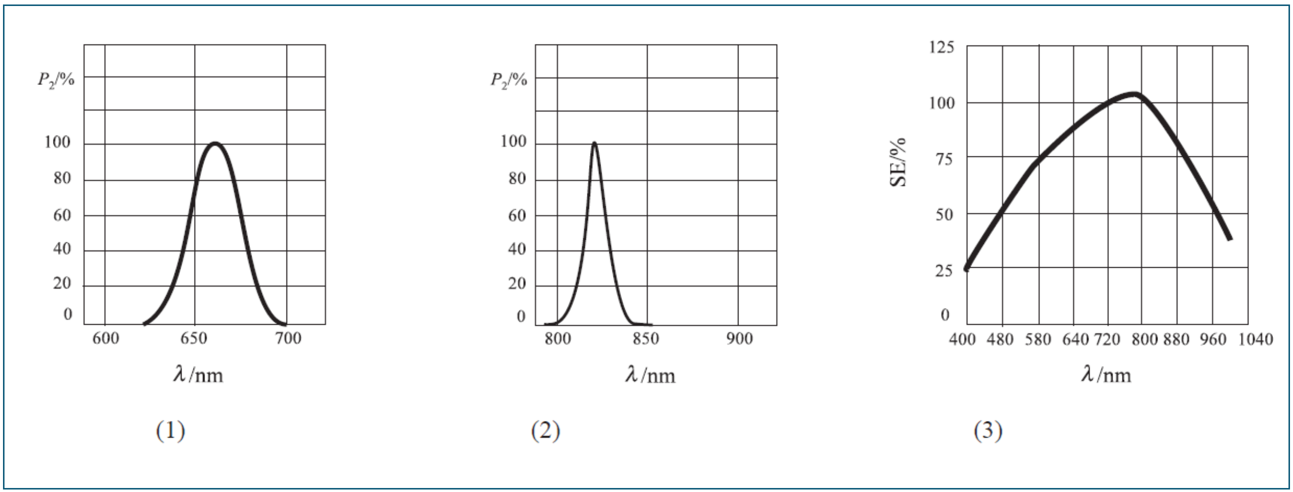


Fig. 17: Spectral characteristics of the LEDs and the photo diode

(1) Radiation characteristic of the LED 665 nm (rel. optical power P_2/%)
(2) Radiation characteristic of the LED 820 nm (rel. optical power P_2/%)
(3) Spectral sensitivity of the SE photodiode

736 425 Set of FSMA cables

The set of cables contains silica glass fiber cables of the type HCS 200/230 and plastic fiber cables of the type PMMA 980/1000. All of the cables are equipped on both sides with FSMA connectors.

- Two glass fiber cables in 5/50 m length
- Two plastic fiber cables in 5/50 m length

Attention!

The polished fiber end surfaces of the HCS200/230 glass fibers are sensitive to impact. For this reason FSMA connectors are equipped with a protective cap after mounting on the cables. During the experiment be careful to avoid any direct impact to the connector end surfaces, e.g. contact to the table top or similar. The PMMA cables are less sensitive in this respect. The range/bandwidth product of the HCS fibers used is depicted in Fig. 18.

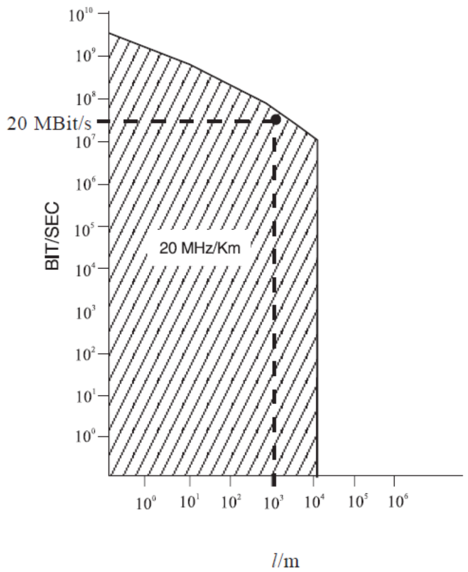


Fig. 18: The range/bandwidth product of the HCS fiber

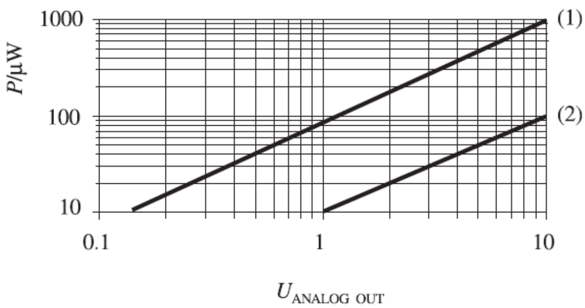


Fig. 19: Calibrate curve to determine the absolute light power P2 from the output voltage of the transimpedance amplifier of the fiber optic adapter

(1): LED 665 nm

(2): LED 820 nm

736 415 Fiber micropositioner

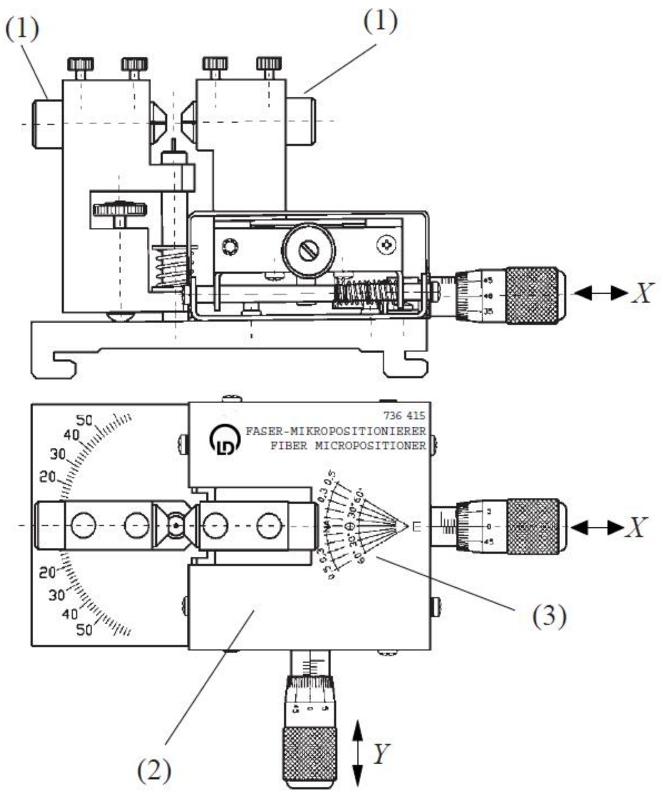


Fig. 20: The fiber micropositioner from front and side view
(1) Fiber mount
(2) Micropositioner basic unit with XY-micrometers and height adjustment (Z-axis)
(3) Scale for approximate determination of the aperture angle θ_0 ($\theta_0 = 2\ \theta_A$) and numerical aperture (NA)

This device is used to investigate axial separation and lateral offset of fiber optic connections. The numerical aperture and the acceptance angle can be determined quantitatively with the built-in angular positioner (angular offset). By employing the interchangeable fiber mounts both bare fibers and fibers with FSMA connectors can be measured.

Technical data

- Offset of the X- and Y-axis of a fiber each by approx. 8 mm with the micrometer.
- Displace the Z-axis using thumb screw.
- Scale for quick reading of numerical aperture and acceptance angle

736 416 Mode scrambler

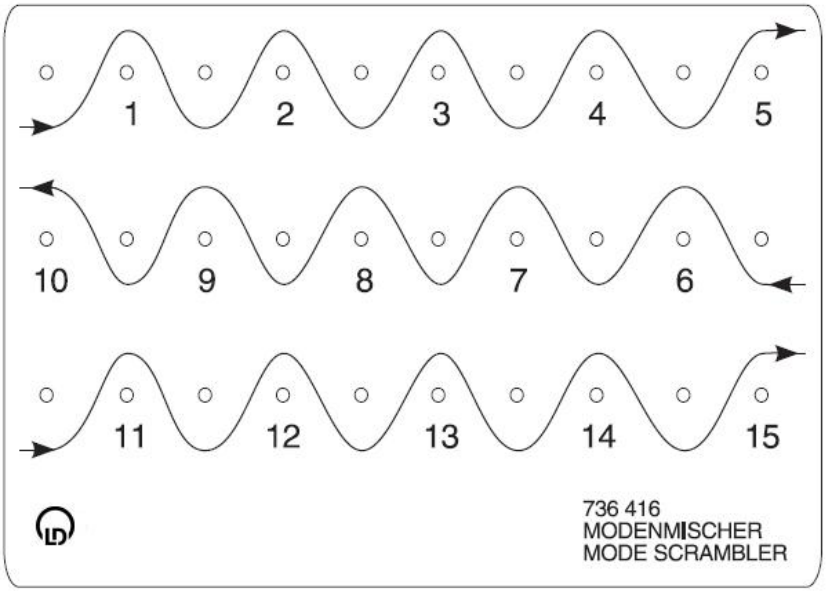


Fig. 21: The mode scrambler

The device consists of a plastic platform on which rows of screws have been installed at equal distances. This allows 15 specifically defined bends to be applied to the fiber optic cables. The power of the higher modes or cladding modes is primarily distorted at the bending points. After setting up the mode scrambler an equal mode distribution (EMD) prevails on the optical fiber. Four large and small cable binders are supplied within the scope of supply of the mode scrambler. For the experiments, see book 564 482.

736 429 Fiber optic microscope

Fig. 22: Fiber optic microscope
(1) Eye piece
(2) Focusing knob
(3) FSMA adapter (aluminum rotary part)
(4) Illumination
(5) Loose fiber adapter

Note

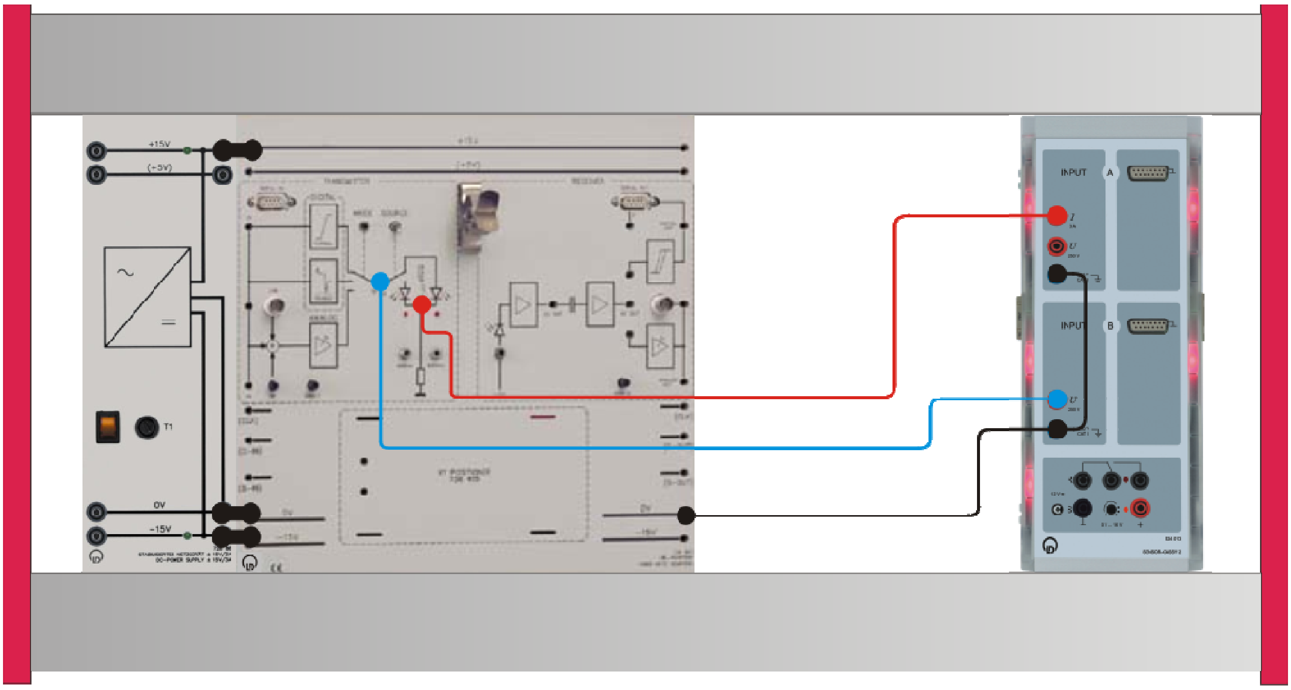
- Insert the FSMA adapter (aluminum element) into the transparent viewing window.
- The illumination is activated automatically by unfolding the microscope. In order to spare the batteries, please make sure that you close the microscope after use.
- Loose fiber adapter for checking the fiber end surfaces of bare PMMA sections. Only tighten when necessary.

Characteristics of the LEDs

Material

Qty.	Cat.-no.	Designation
1	736 401	Fiber Optic Adapter
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
1	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
2	500 614	Safety Connection Lead 25 cm, black
4	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Carrying out the experiment



Presettings

- Fiber optic adapter
  OP: left limit
  MODE: ANALOG
  SOURCE: 665 nm.

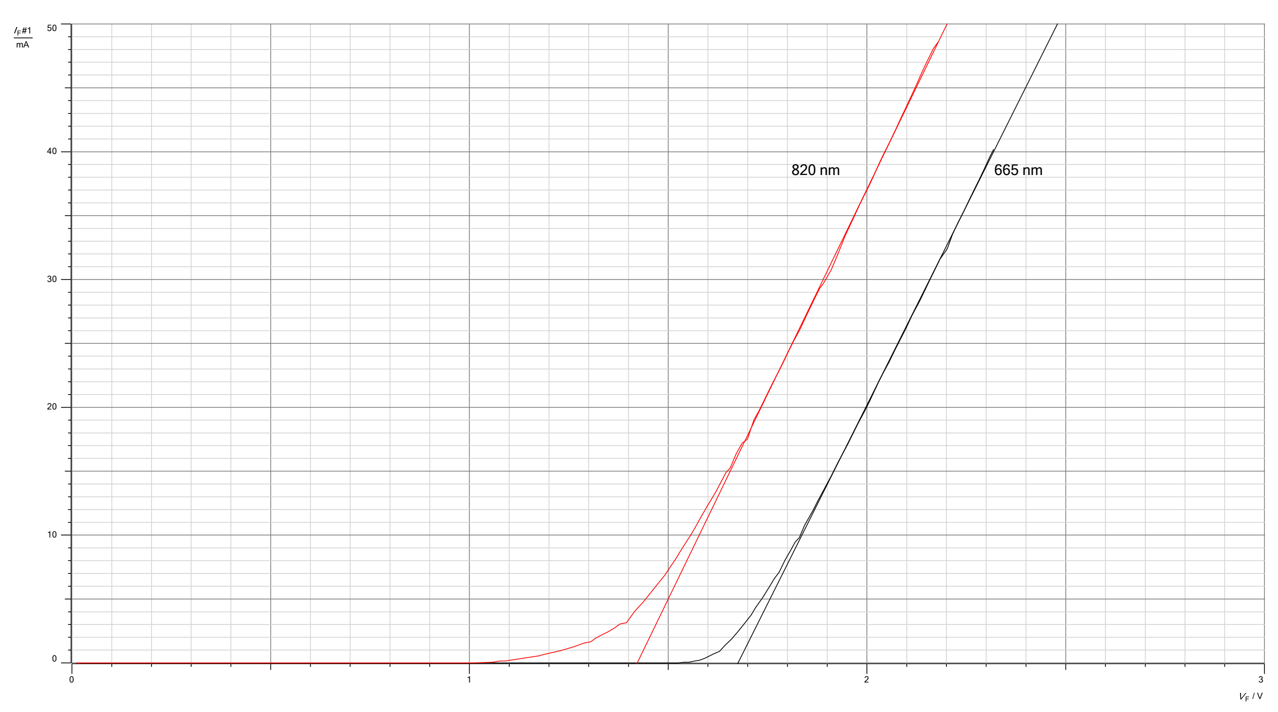
- Set up the experiment as shown.
- Load the CASSY Lab 2 example LED_Char.labx.
- Select the representation *IV-Characteristic*.
- Start the measurement by pressing *F9*.
- Open the instruments V_F and I_F.
- Increase the forward voltage U_F by slowly turning the potentiometer *OP* to the right. In the range where the current increases abruptly slow down accordingly.
- **Note:** The forward voltage U_F and current I_F are measured at the sockets V_{LED} or I_{LED} x 10 Ω. The forward current I_F is converted into a voltage across the 10 Ω resistor.
- Stop the measurement by pressing *F9*.
- Repeat the measurement for 820 nm.
- Sketch the current-voltage characteristics (*IV*) of both LEDs commonly in one diagram.
- Determine the parameters of the LEDs with CASSY Lab.
- Make a right click into the graphic area and select: *Fit Function Best-fit / Straight Line*. The threshold voltage U_S is obtained from the point where the tangent intersects the voltage axis. The differential resistance r_F of the LEDs is obtained from inverse value of the slope.
- Interpret the results.
- Display the graph of the electrical input power P_1 absorbed for both LEDs, by clicking on the representation *PI-Characteristic. Note:* $P_1 = I_F \times U_F$

LED	**665 nm**	**820 nm**
Threshold voltage V_S		
Differential resistance r_F		

Variant

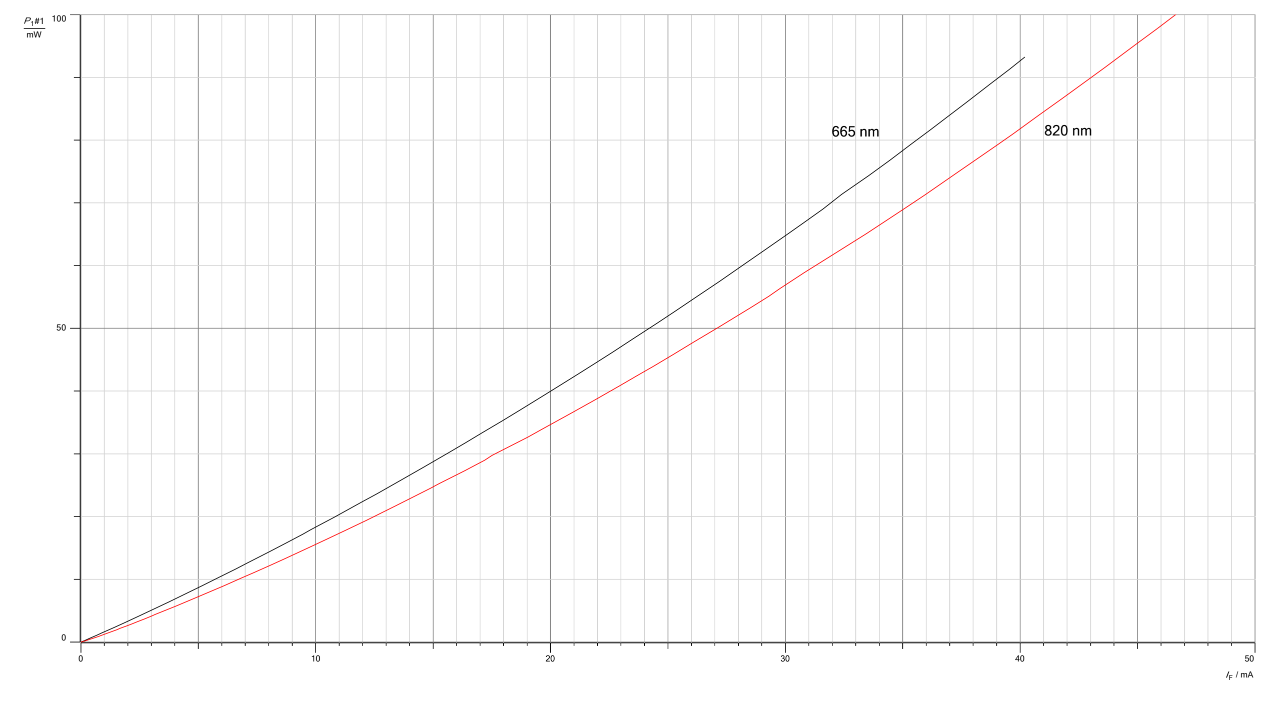
- Measuring of the optical power P_2 as a function of the forward current I_F of the LEDs and discussing the electro-optical efficiency.

Results



IV-Characteristic of the LEDs (665 nm/820 nm)

LED	665 nm	820 nm
Threshold voltage V_S	1.68 V	1.42 V
Differential resistance r_F	16.1 Ω	15.6 Ω



PI-Characteristic of the LEDs (620 nm/820 nm)

Observations

The LEDs block practically until the threshold voltage V_S is reached (i.e. $I_F = 0$ for $V_F < V_S$). Exceeding the threshold voltage, the diode current rises abruptly. If you apply a tangent to the steep section of the IV-characteristic, then you obtain the threshold voltage V_S where the tangent intersects the voltage axis. The differential resistance r_F of the LEDs is calculated based on the slope of the IV-characteristic.

On the displacement of the two characteristics

Direct semiconductors exhibit radiant recombination. By this we mean the neutralization of electron-hole pairs in a pn-structure when a photon is transmitted. The released photon has an energy level given by its energy gap in accordance with Eq. 10. The smaller the energy gap E_G, the lower the photon`s energy (and frequency) and thus the greater is the wavelength of the emitted photon (Eq. 1). The IV-characteristic gives a threshold voltage V_S that is smaller for λ = 820 nm than for λ = 665 nm. The electrical power consumption P_1 of the LED is almost linearly dependent on the diode current. This holds true provided the differential resistance r_F is neglected.

Attenuation in optical fibers

Measurement methods to determine attenuation

Attenuations can be measured either according to the throughput method or according to the principle of pulse reflectometry. Throughput measurements require access to both ends of the cable (normally not possible for installed cables). The pulse reflectometry only needs measurements on one end of the cable but also requires considerably more measurement equipment. One standard throughput measurement is performed according to the cutback method. Here the optical power P_2 is measured at one end of a known cable length. Then the cable is cut back to a few meters in length and the transmitted optical power is determined again. This method is used to keep the launch conditions the same. This advantage is offset by the disadvantage that the measurements are not without damage. Every measurement irreversibly means the loss of a section of fiber. After a finite number of measurements the fiber becomes too short. This procedure is too expensive for student training. For the purpose of experimentation attenuation measurements are performed as throughput measurements on optical fibers of different length, which are equipped with plug connectors on both ends. A typical parameter for an optical fiber is the attenuation *a* per unit length (e.g. km). In the experiment the attenuation is measured for a difference length Δl = 45 m (a_{45}). Thus the attenuation *a* per km has to be corrected by the factor 1000/45:

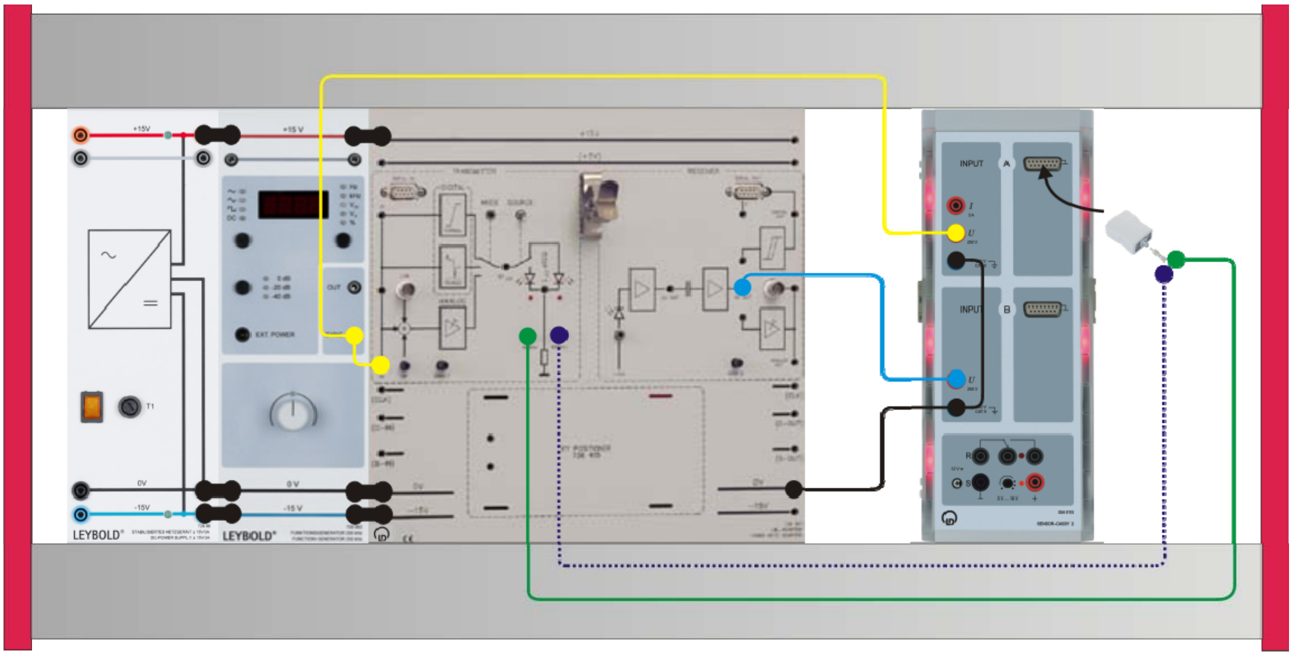
$$a = \frac{1000}{45} \cdot a_{45}\ dBkm^{-1} \qquad (3.1)$$

Material

Qty.	Cat.-no.	Designation
1	736 401	Fiber Optic Adapter
1	736 425	Set of FSMA Optical Fibers
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
1	726 962	Function Generator 200 kHz
1	524 0512	Optical Power Sensor S
1	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
1	500 592	Set of 10 Safety Bridging Plugs with Tap, black
2	500 614	Safety Connection Lead 25 cm, black
4	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Carrying out the experiment

Attenuation per unit length



- Set up the experiment
- Set the function generator to: 2 kHz, use the TTL out (Sync).
- Set the fiber optic adaptor to: Mode = norm, Source = 665 nm.

PMMA

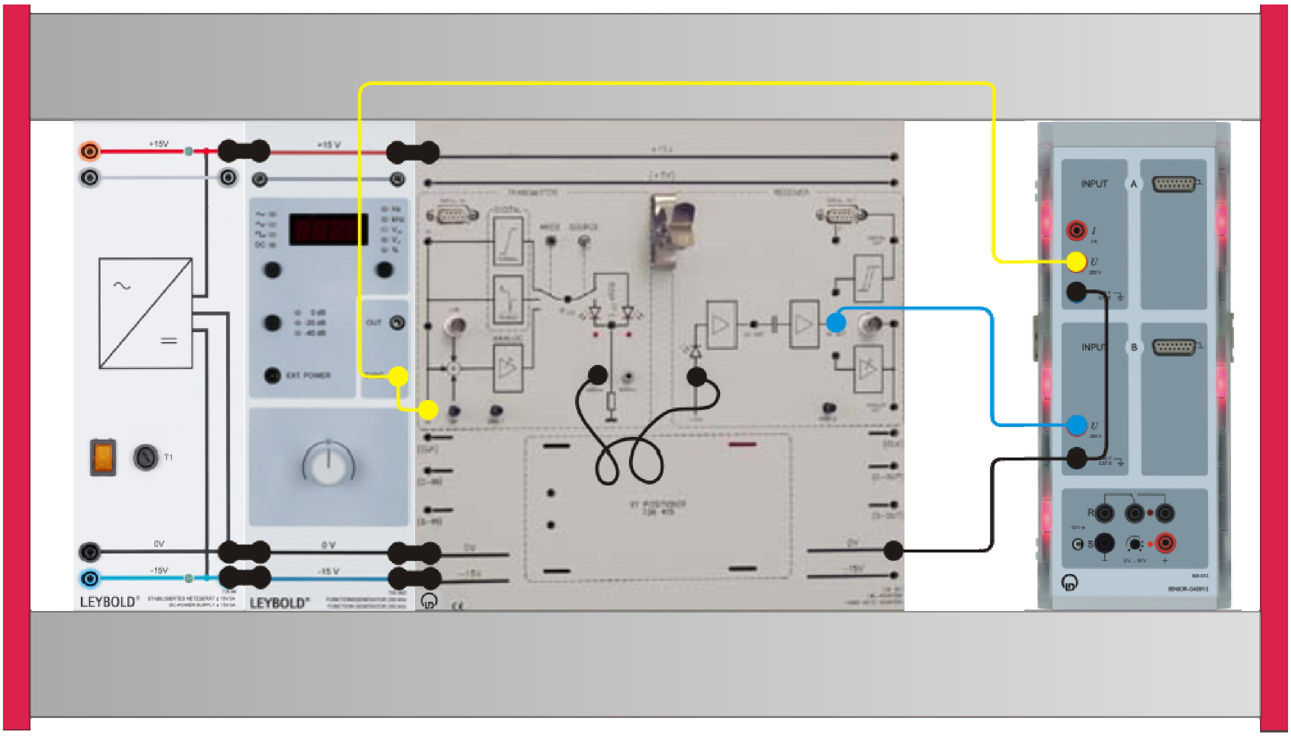
- Connect the PMMA fiber (l = 5 m) to the LED 665 nm and to the optical power sensor.
- Load the CASSY Lab example FiberLoss.labx.
- Calibrate the optical power sensor. For that make a right click into the instrument optical power PA1 / Settings → 0 ←.
- Close settings.
- Replace the PMMA fiber (l = 5 m) by the l = 50 m.
- Read the attenuation on the instrument *Attenuation 45*.
- Enter the value into the table.
- Repeat the experiment with PMMA-fibers for 820 nm.

HCS

- Connect the HCS fiber (l = 5 m) to 820 nm and to the optical power sensor.
- Calibrate the optical power sensor. For that make a right click into the instrument optical power PA1 -> Settings → 0 ←.
- Close settings
- Replace the HCS-fiber (l = 5 m) by the l = 50 m
- Read the attenuation on the instrument *Attenuation 45.*
- Enter the value of the attenuation into the table.
- Repeat the experiment with HCS-fibers for 665 nm.

	Attenuation	
	PMMA	HCS
665 nm		
820 nm		

Display of the received signals



- Set up the experiment
- Set the function generator to: 2 kHz, use the TTL out (Sync).
- Set the fiber optic adaptor to: Mode = norm, Source = 665 nm.

PMMA

- Connect the LED 665 nm and the photo detector (TIC) with the PMMA-fiber l = 5 m.
- Load the CASSY Lab 2 example Attenuation.labx.
- Start the measurement by pressing *F9*.
- Repeat the measurement for the PMMA-fiber l = 50 m.
- Sketch both measurements within a single diagram.
- Repeat the measurements for the LED 820 nm.
- Give an interpretation.

HCS

- Repeat the experiment for the HCS-Fibers with l = 5/50 m.
- Again use LED 665 nm and LED 820 nm.

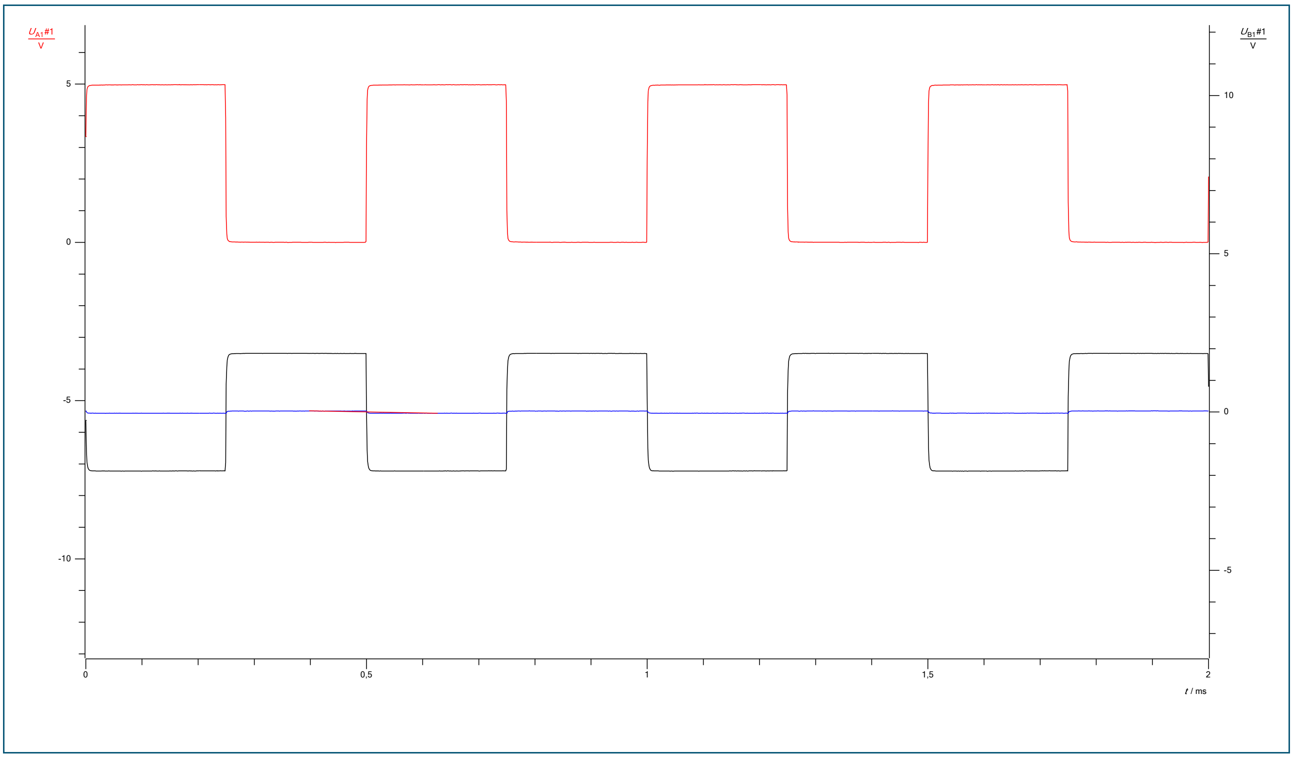
Results

Attenuation in PMMA and HCS per unit length

	Attenuation	
	PMMA	HCS
665 nm	349.8 dB/km	13.2 dB/km
820 nm	Not determined > 500 dB/km	dB/km

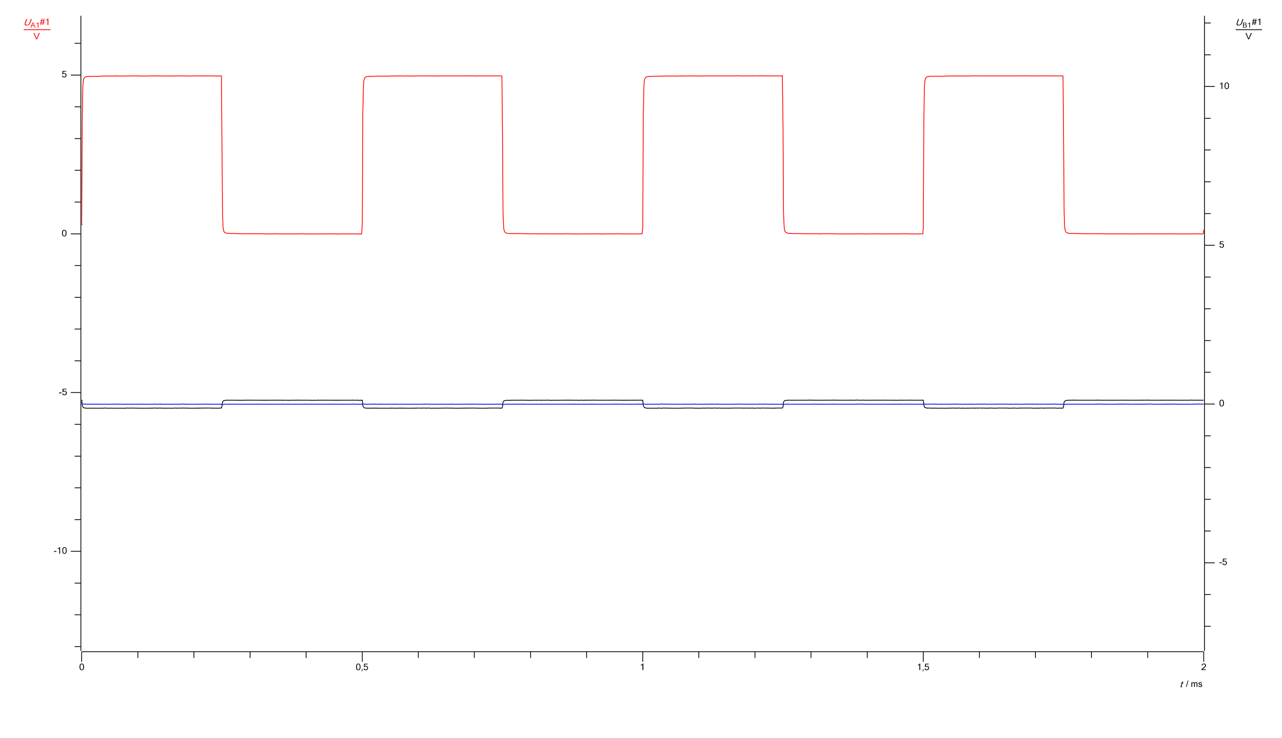
Display of the received signals using PMMA-fibers

PMMA **λ = 665 nm**



Red: Modulating signal unipolar, TTL, 2 kHz
Black: PMMA fiber l = 5 m, bipolar, approx. 3.7 V_{pp}, inverse polarity
Blue: PMMA fiber l = 50 m, bipolar, approx. 0.1 V_{pp}, inverse polarity

PMMA **λ = 820 nm**

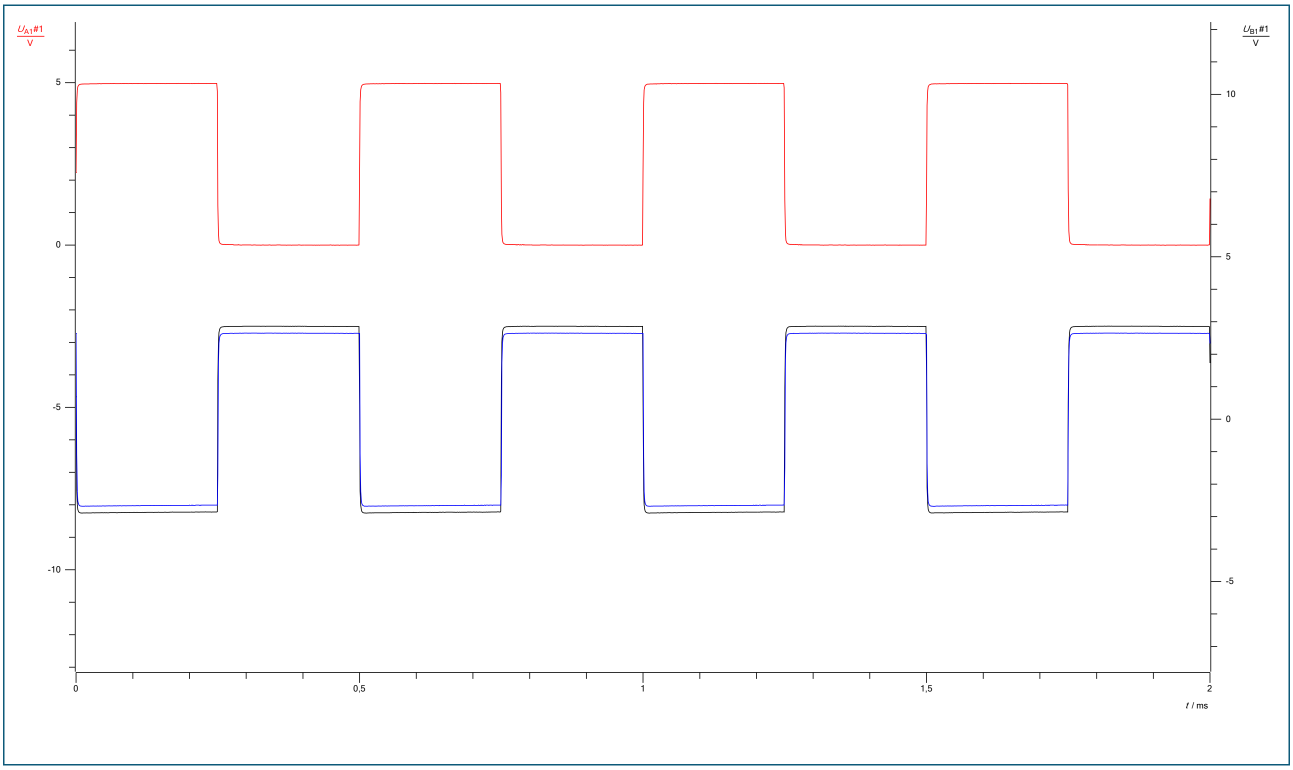


Red: Modulating signal unipolar, TTL, 2 kHz

Black: PMMA fiber l = 5 m, bipolar, approx. 0.2 V_{pp}, inverse polarity

Blue: PMMA fiber l = 50 m, bipolar, no signal detectable (approx. 0 V_{pp})

HCS **λ = 820 nm**



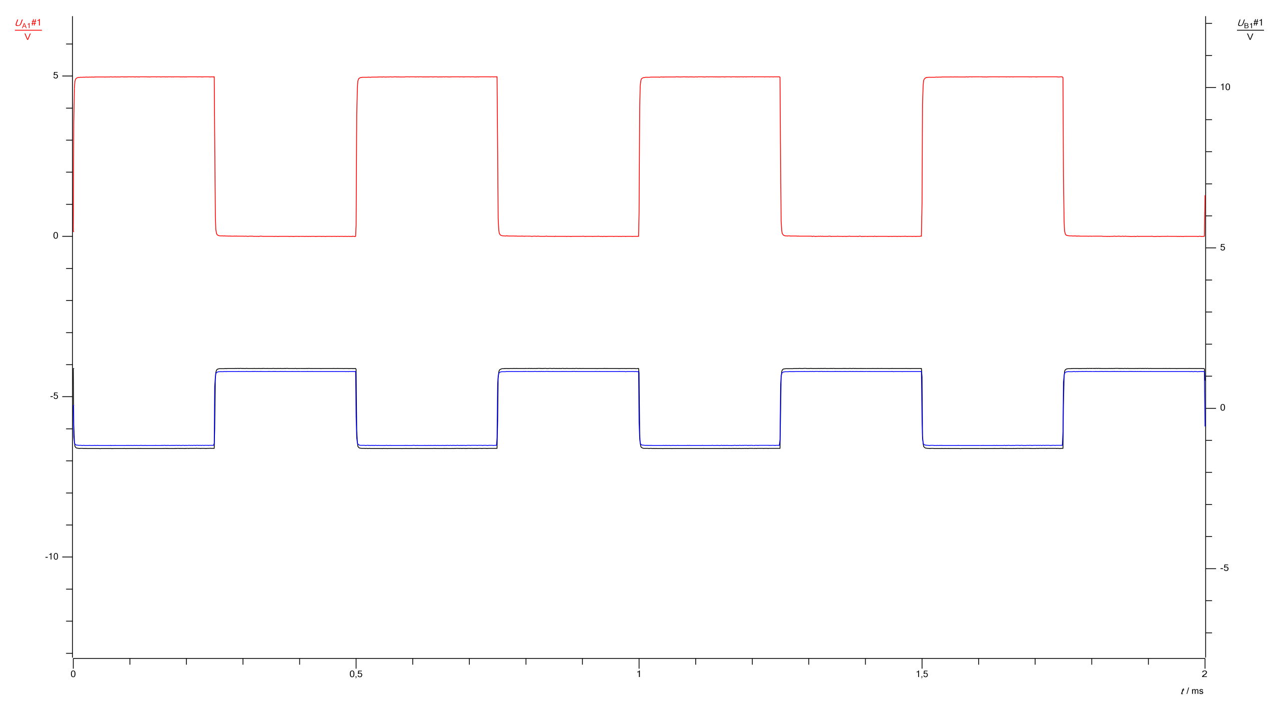
Red: Modulating signal unipolar, TTL, 2 kHz

Black: HCSA fiber l = 5 m, bipolar, approx. 5.8 V_{pp}, inverse polarity, saturation effect

Blue: HCS fiber l = 50 m, bipolar, approx. 5.4 V_{pp}, inverse polarity, strong signal nearly saturated.

The cable lengths are too short to give a strong attenuation.

HCS **λ = 665 nm**



Red: Modulating signal unipolar, TTL, 2 kHz
Black: HCS fiber l = 5 m, bipolar, approx. 2.5 V_{pp}, inverse polarity
Blue: HCS fiber l = 50 m, bipolar, approx. 2.2 V_{pp}, nearly no difference than the output at l = 5 m.

Interpretation

Measurements of the received signal with HCS 200/230 do not give significant deviations of the values for 5 m or 50 m lengths respectable. For these relative short lengths of optical fibers, attenuation plays only a minor role in the total losses of the cable. Due to the fluctuations in the connector assembly it is even possible to measure a stronger received signal on the longer cable. This seems to be a contradiction, but takes only into account the losses in the connectors. Attenuation in fibers of small lengths cannot be determined exactly by the cut back method.

Notes

- With exceeding optical power levels, transmission disturbances can arise.
- These disturbances are stronger for small cable lengths (5 m) and in peaked mode.
- In normal operating mode the light power of the LEDs is smaller than in peaked power mode.
- Phase shift between the modulating signal and the receiving signal arises only at AC out.

Digital transmission methods

In practice, distortions caused by bad or faulty connections can be introduced into the transmission link. The effect of these kinds of distortions is a drop of optical power at the photo diode resulting in the attendant problems involving threshold value recognition by the receiver. The statistical emergence of bit errors depends on the signal-to-noise ratio SNR at the optical receiver as shown in Fig. 4.1.

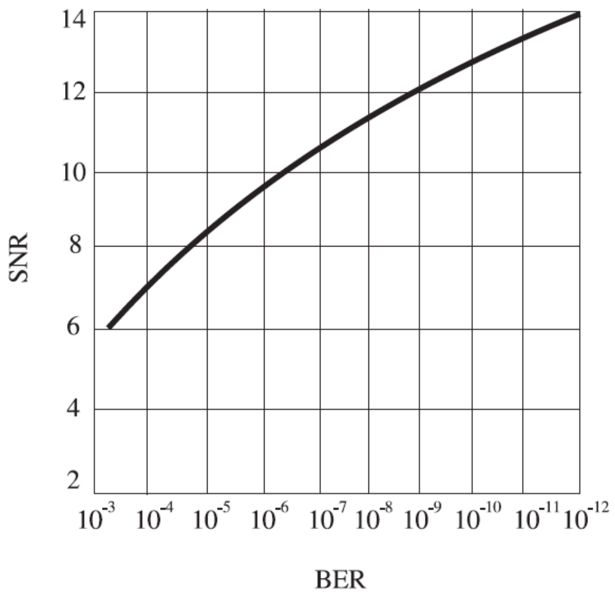
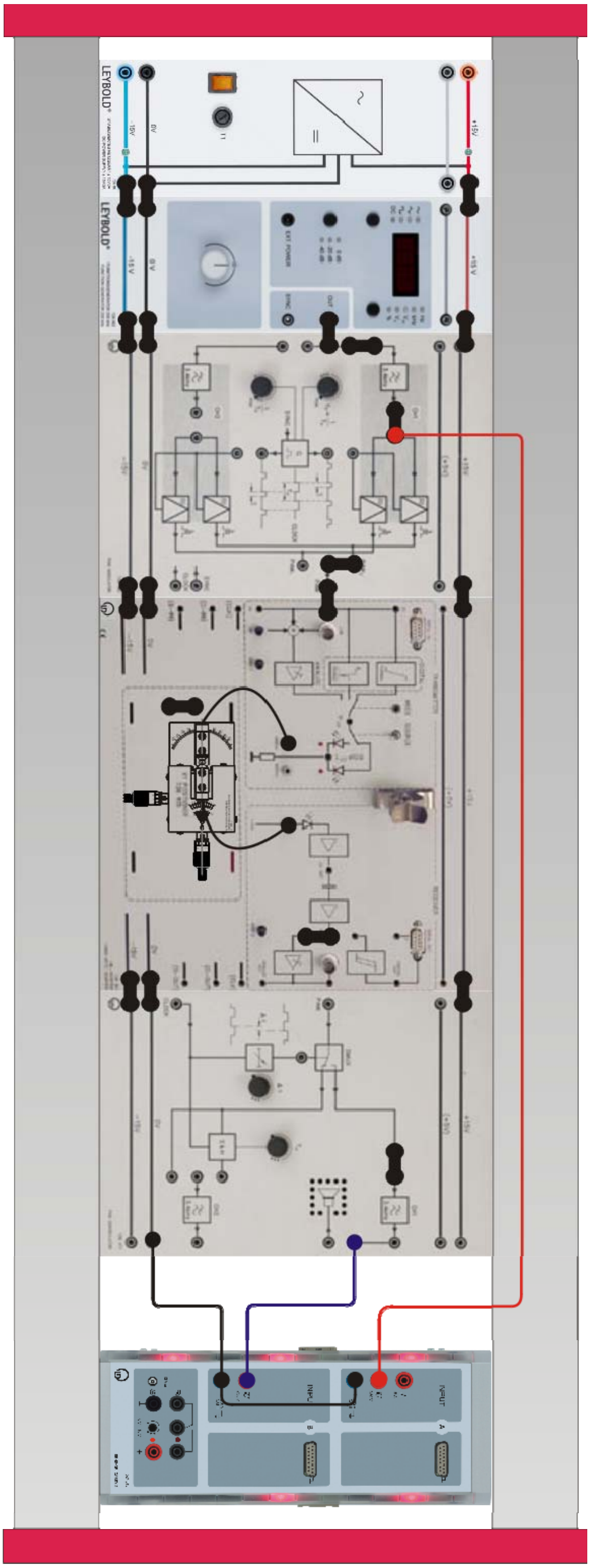


Fig. 4.1: Dependency of the bit error rate BER on the SNR

Material

Qty.	Cat.-no.	Designation
1	736 061	PAM Modulator
1	736 071	PAM Demodulator
1	736 101	PCM Modulator
1	736 111	PCM Demodulator
1	736 401	Fiber Optic Adapter
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
2	726 962	Function Generator 200 kHz
4	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
1	500 592	Set of 10 Safety Bridging Plugs with Tap, black
2	500 614	Safety Connection Lead 25 cm, black
4	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Transmission of PAM via fiber micropositioner

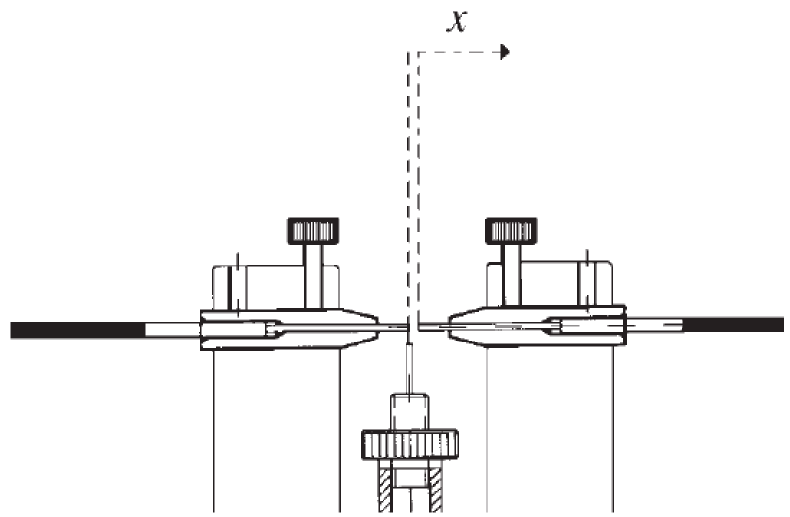


- Set up the experiment as shown.
- Function generator: sine, 500 Hz, 10 V_{pp}.
- Use fiber sections equipped with FSMA connectors on one end which have been included with the fiber micropositioner, see detailed sketch.

Calibration

- Set the fiber optic adaptor to: Source = 665 nm. Mode = analog.
- Set the PAM Modulator to: τ/T_P → PCM (maximum right), f_P → maximum left)
- Load the CASSY Lab 2 example PAMCal.labx.
- Start the measurement by pressing *F9*.
- Display the receiving signal at Analog Out of the fiber optic adapter.
- Adjust OP, GAIN 1, GAIN 2 until the modulating signal at the output of the channel filter CH 1 is coincident with the output signal at Analog OUT.

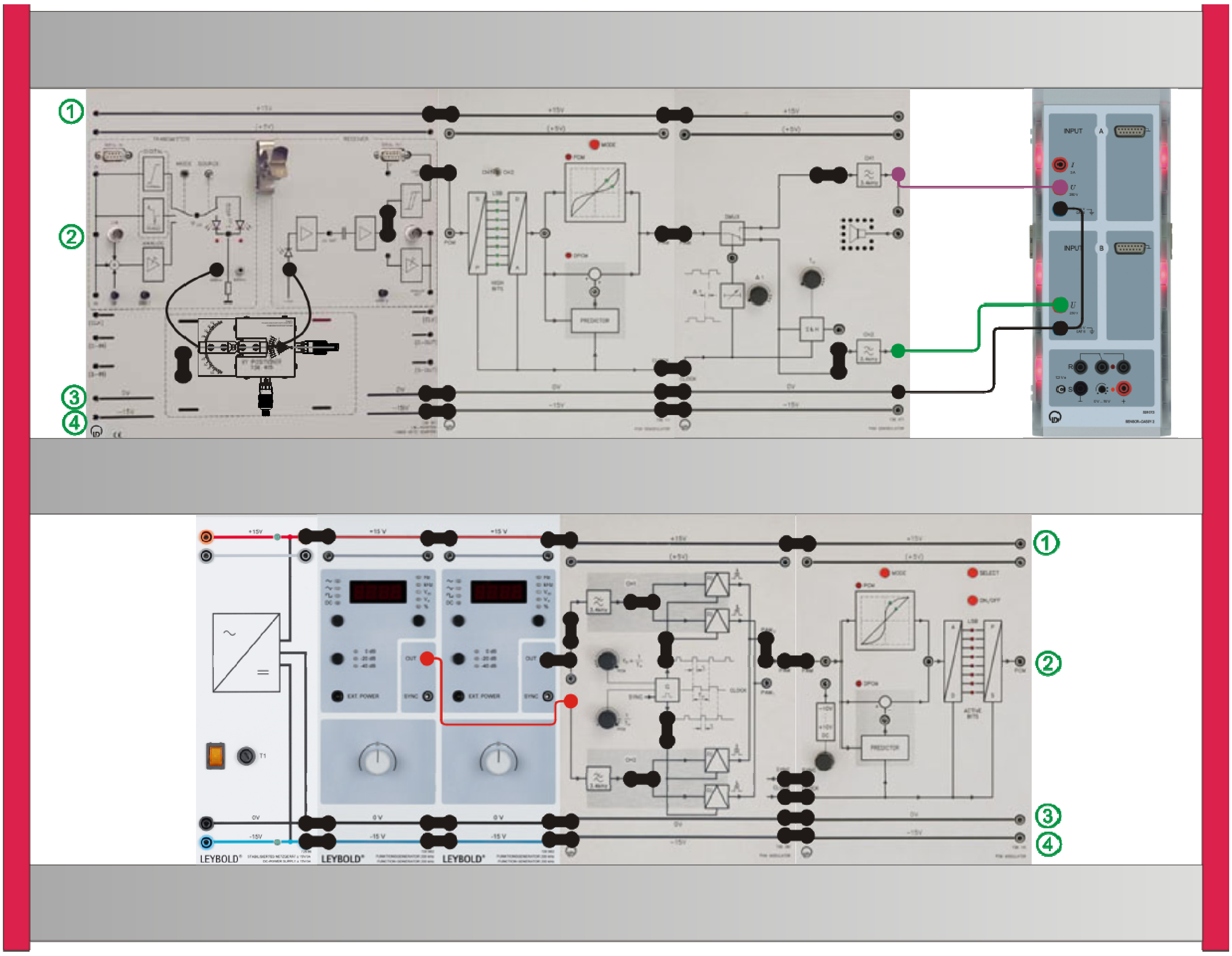
- Fiber micropositioner: Set X-manipulator to zero.
- If necessary adjust the fiber ends (X) in the holder, until you obtain again coincidence between the modulating signal and the PAM signal.
- Stop the calibration measurement by pressing *F9*.



Detailed sketch on how to produce transmission distortions with the fiber micropositioner

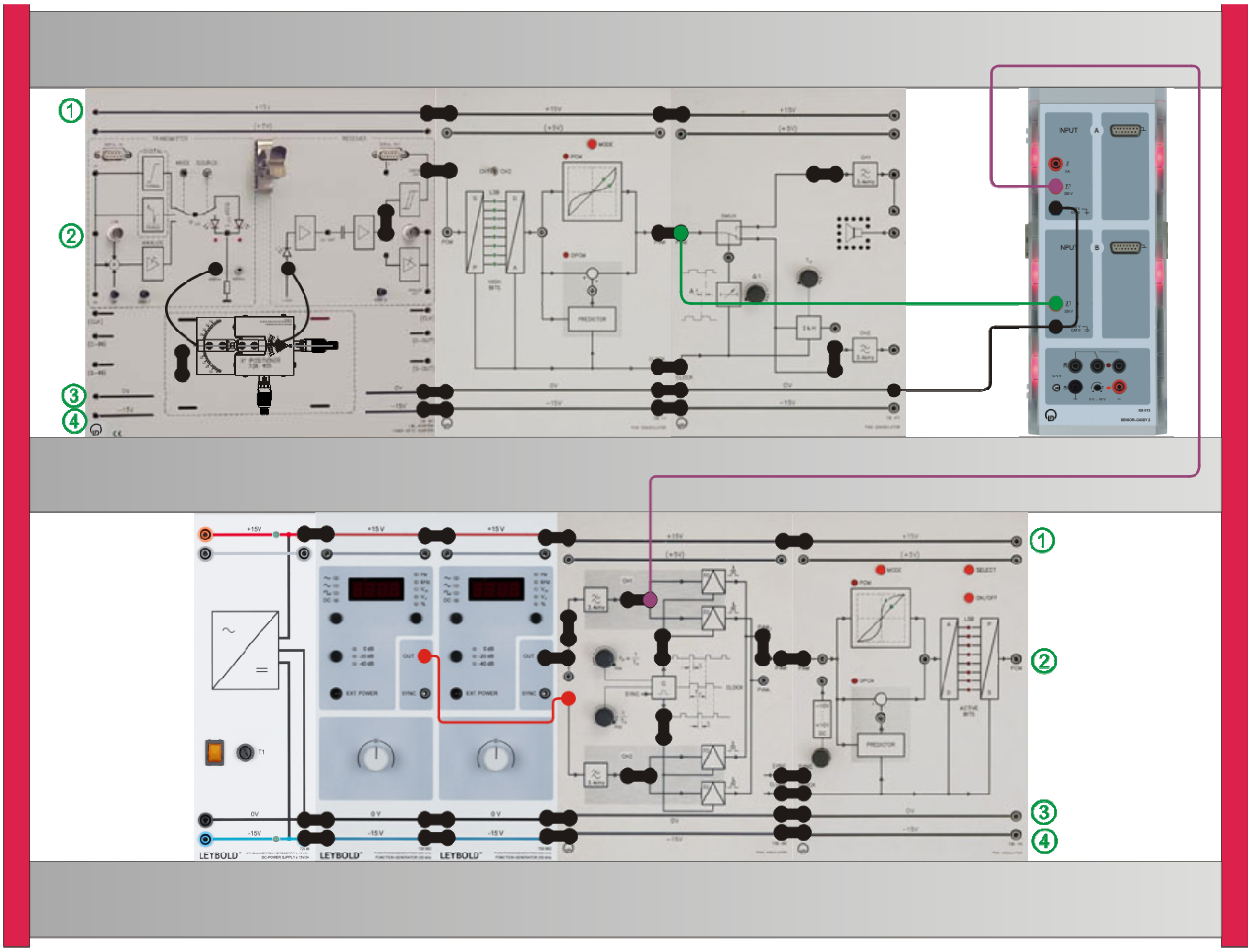
- Connect channel B to the output of the PAM demodulator as shown.
- Load the CASSY Lab 2 example PAMModDem.labx.
- Start the measurement by pressing *F9*.
- Sketch the modulating signal and the demodulated signal for an air gap x = 0 mm at the micropositioner.
- Repeat the measurement for a longitudinal setting of 1.0 mm respectively 2.0 mm.
- For that turn the X-micrometer of the fiber micropositioner to 1.0/2.0 mm. **Note:** 1 mm means 2 turns of the micrometer screw!
- Discuss your results.

Transmission of PCM via fiber micropositioner



- Set up the experiment as shown.
- Function generator 1: triangular, 250 Hz, 15 V_{pp}.
- Function generator 2: sine, 500 Hz, 10 V_{pp}.
- Set the PAM Modulator to: τ/T_P → PCM (maximum right), f_P → PCM (maximum right)
- Fiber optic adaptor: Mode = normal, source = 665 nm. **Note:** Set a bridging plug from AC-out to the comparator. Use Digital Out.
- Fiber micropositioner: Set X-manipulator to zero.
- Load the CASSY Lab 2 example PAMModDem.labx.
- Start the measurement by pressing *F9*.
- Increase the longitudinal separation X of the fibers. If necessary add angular misalignment until the PCM transmission gets disturbed.
- Sketch the demodulated signals of CH 1 and CH 2 at the outputs of the PAM demodulator.
- Give an interpretation of the results.

Time division multiplex signals

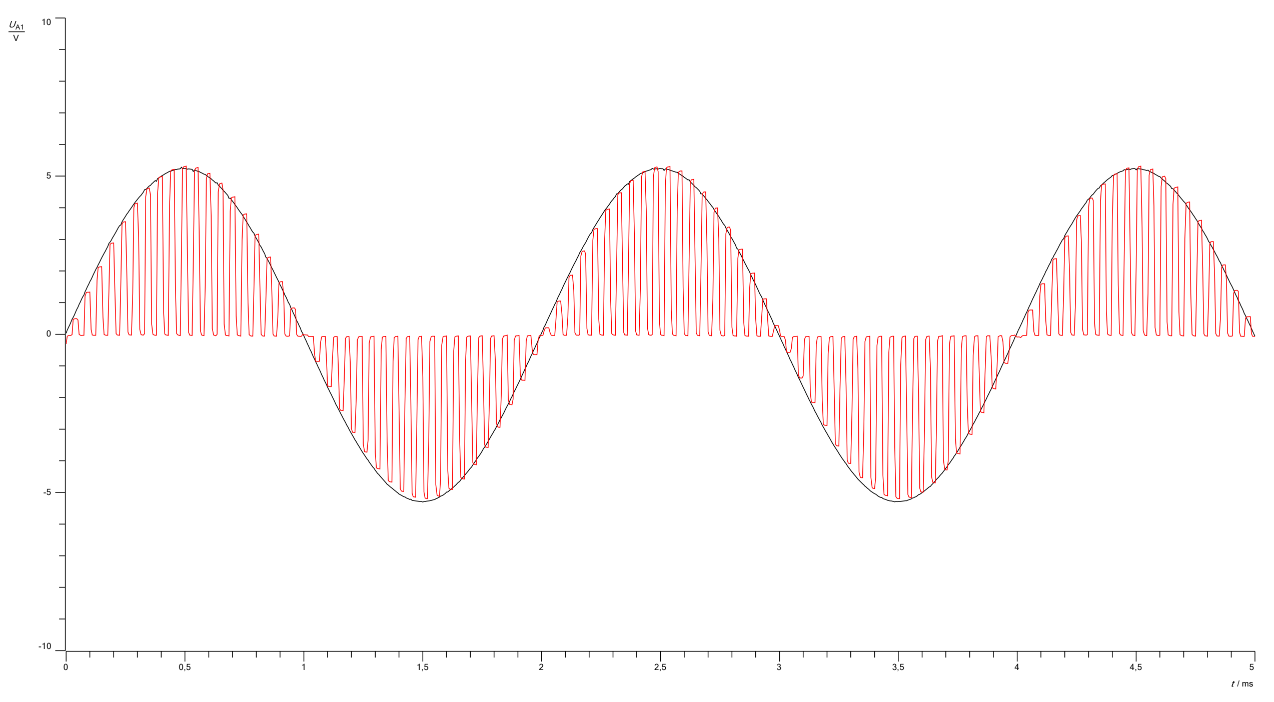


- Set up the experiment as shown.
- Function generator 1: triangular, 250 Hz, 15 V_{pp}.
- Function generator 2: sine, 500 Hz, 10 V_{pp}.
- Set the PAM Modulator to: τ/T_P → PCM (maximum right), f_P → PCM (maximum right)
- Fiber optic adaptor: Mode = normal, source = 665 nm
- Set the fiber micropositioner to the start conditions for undisturbed PCM transfer. Not critical!
- Load the CASSY Lab 2 example PCMTDM.labx.
- Start the measurement by pressing *F9*.
- Give an interpretation of the results.

Results

Transmission of PAM via fiber micropositioner

Calibration

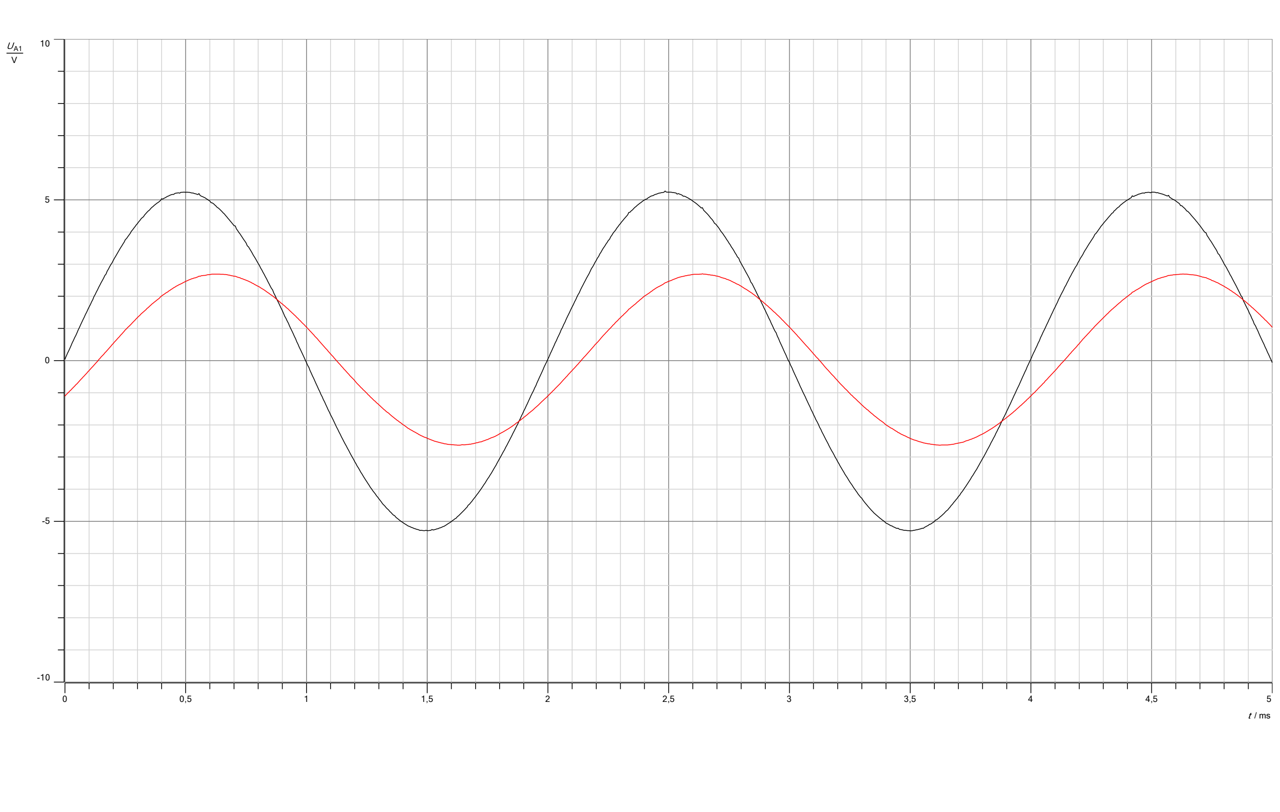


Calibration for PAM with the fiber micropositioner

Black: Modulating signal at the PAM modulator

Red: PAM; signal at Analog out of the fiber optic adapter

PAM-Transmission X = 0.00 mm



Digital transmission of PAM with the fiber micropositioner. Modulating & demodulating signal

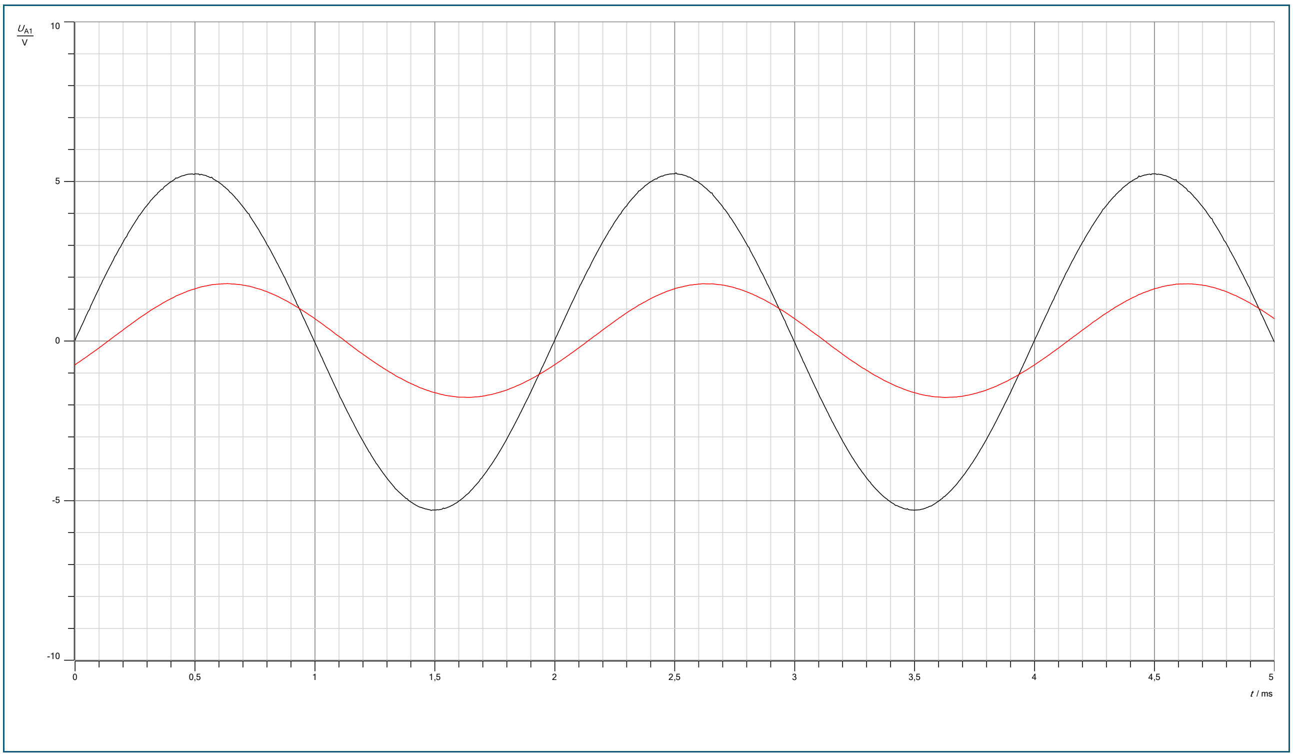
Black: Modulated signal ca. A_M = 10.6 V_{pp}

Red: Demodulated signal, ca. A_D = 5.3 V_{pp}.

Interpretation

- The reduction of the amplitude is a consequence of the sampling process.
- For PAM the amplitude of the demodulated signal is proportional the duty cycle.
- In this case the duty cycle is τ/T_P = 0.5.

PAM-Transmission X = 1.0 mm



Digital transmission of PAM with the fiber micropositioner.

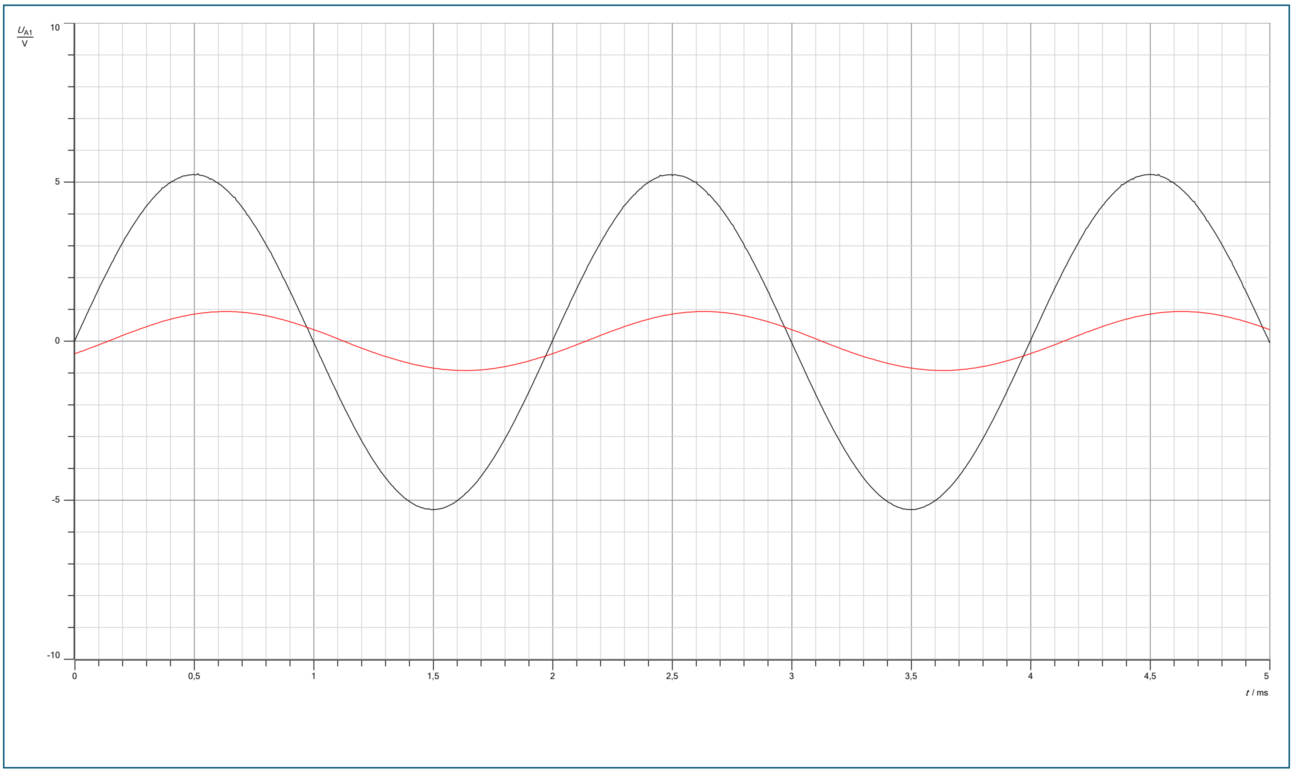
Black: Modulated signal ca. A_M = 10.6 V_{pp}

Red: Demodulated signal, ca. A_D = 3.6 V_{pp}.

Observation

- Demodulated signal becomes smaller.

PAM-Transmission X = 2.0 mm



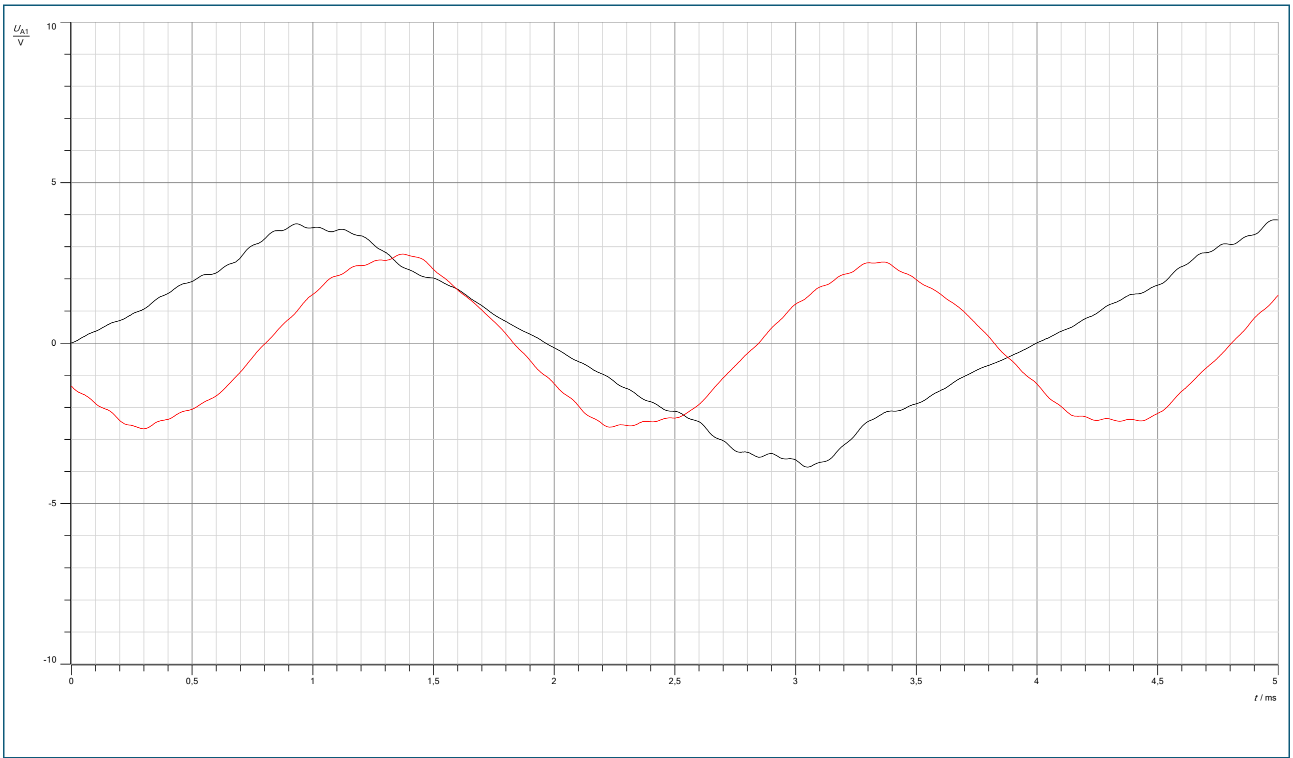
Digital transmission of PAM with the fiber micropositioner

Black: Modulated signal ca. A_M = 10.6 V_{pp}
Red: Demodulated signal, ca. A_D = 1.9 V_{pp}.

Observation

- Demodulated signal becomes even more smaller.

PCM-Transmission X = 0.0 mm



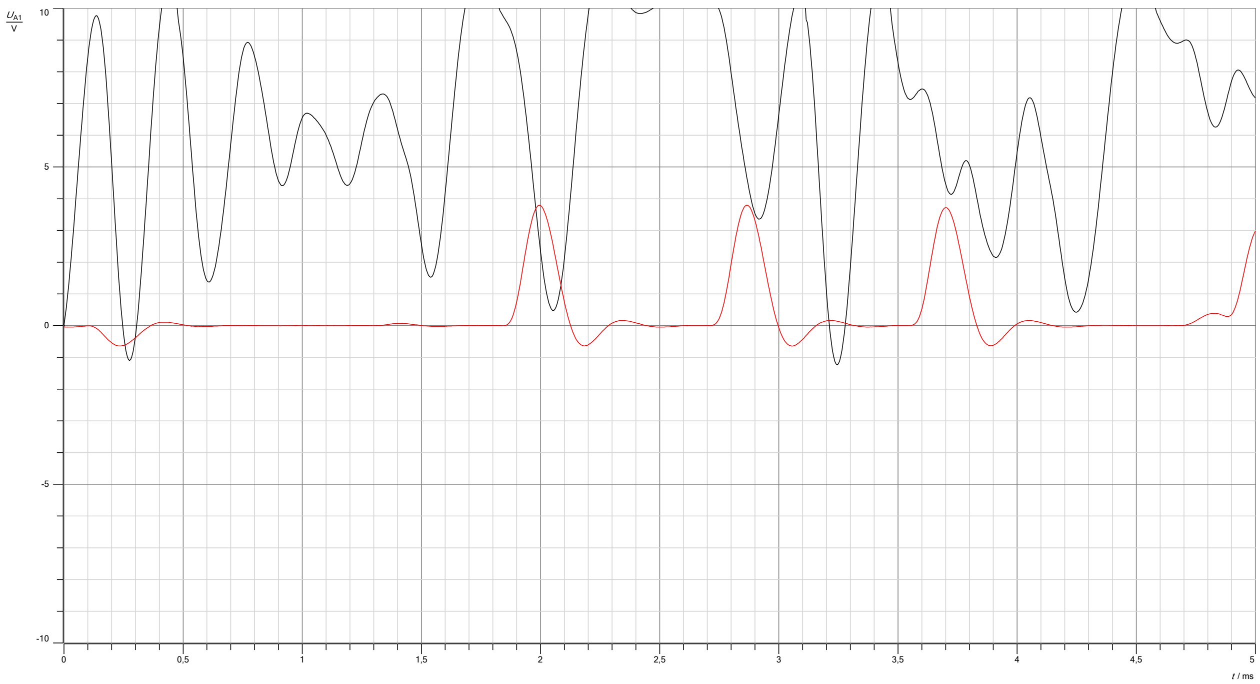
Digital transmission of PCM with the fiber micropositioner

Black: Demodulated triangular signal
Red: Demodulated sinusoidal signal

Observations

- Sine: 5.3 V_{pp} (approx.), loss in amplitude due to sampling process $\tau/T_P = 0.5$
- Triangle: 7.5 V_{pp} (approx.)
- Due to the quantization process the demodulated signal is more distorted than the pure PAM-transmission.

PCM-Transmission, disturbed



Digital transmission of PCM with the fiber micropositioner

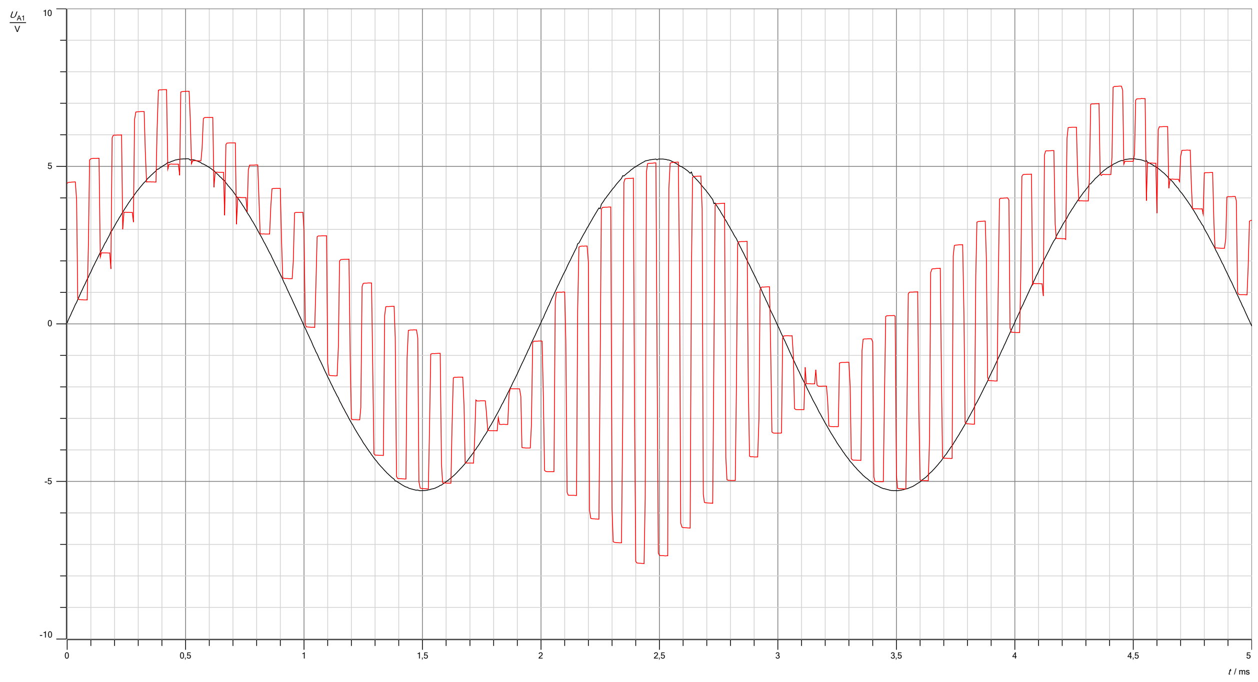
Black: Modulated signal, channel 1. Totally distorted

Red: Demodulated signal, channel 2.Totally distorted

Interpretation

- With maximum longitudinal separation approx. 10 mm and additional angular misalignment the transmission of the digital modulated signal finally breaks down.

Time division multiplex signals



Digital transmission of PCM with the fiber micropositioner. Modulating & time division multiplexing signals.

Black: Modulating signal of channel 1

Red: Time division signal for two channels. CH 1: sine, CH 2: triangular

Observations

PCM data transmission using optical fibers is tolerant against fiber misalignment.

The enlargement of the longitudinal spacing *X* does not cause any change in the demodulated signal up until the critical distance X_{crit} is reached. After exceeding the critical distance X_{crit} the signal-to-noise ratio drops to the point where the bit error rate increases considerably. The demodulated signal now frequently shows considerable distortion. Those typical cracking sounds occur in loudspeakers.

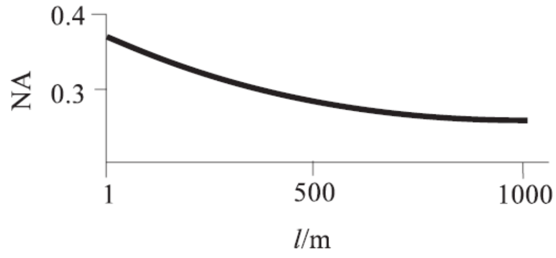
The signal at the output of the PCM demodulator is the time division multiplexing (TDM).

The PAM modulator and PCM demodulator deliver TDM signals.

Determining the numerical aperture

Fundamentals

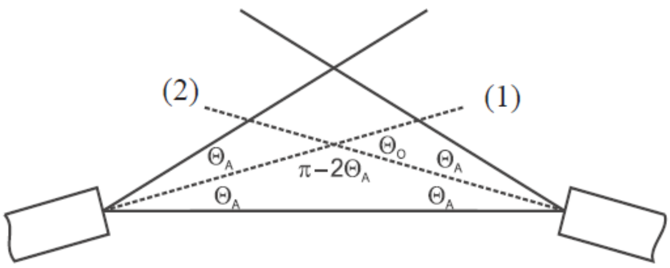
The numerical aperture (NA) is an important parameter in fiber optics. A high NA results in great coupling effectiveness, i.e. incidenting light can easily be coupled into the fiber. Also the losses resulting from bends decrease with increasing numerical aperture. In HCS fibers the numerical aperture is a function of the fiber length. In the case of short fiber lengths a portion of the light is also propagated in the cladding or in higher modes. Due to stronger attenuation for these modes the numerical aperture declines with increasing fiber length.



The numerical aperture (NA) of an HCS fiber as a function of the fiber length

The determination of the numerical aperture with the aid of the fiber micropositioner (736 415), is a simplified method based on the measurement of the angle θ_O of the optical axis of two fibers. The axe angle is two times the incident angle on the fiber surface. Because open fiber ends do not radiate equally into all directions (no omnidirectional radiation pattern), the acceptance angle Θ_{AC} is reached gradually, without a sharp transition from radiation to non-radiation.

$$\Theta_0 = 2\Theta_A = 2 \cdot \arcsin NA \qquad (5.1)$$



How to measure the acceptance angle Θ_A. (1), (2): Longitudinal axis of the fibers encompass the optical axis angle θ_O

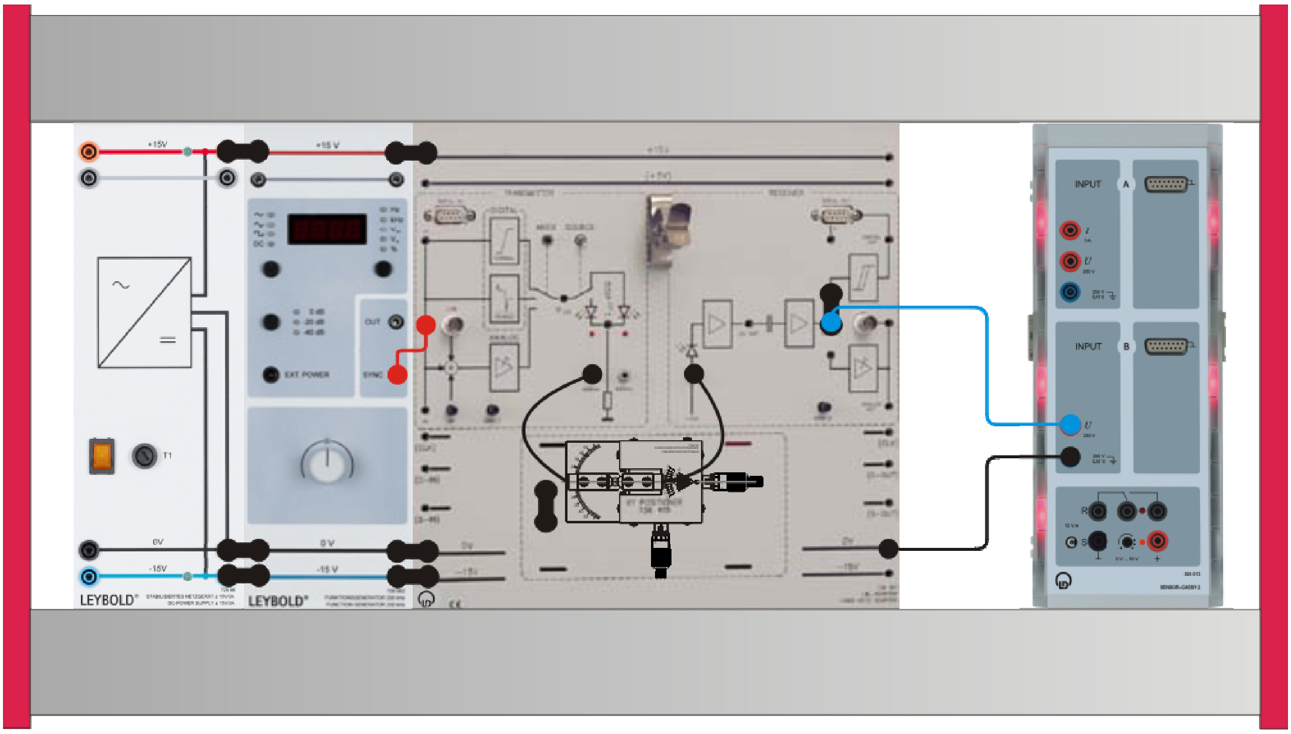
Notes

- This experiment requires some practical experiences with regard to a proper alignment of the angular positioner and the lateral offset.
- The acceptance angle θ_A is determined at the intersection point with -15 dB below the reference intensity at θ_O = 0 dB.
- Although sometimes the intersection point is measured at a threshold of -20 dB (this gives a somewhat greater acceptance angle and higher NA) there is no significant difference in the procedure.
- The acceptance angle θ_A can be estimated directly from the angular scale of the micropositioner.
- For fixing fibers with FSMA-connectors to the fiber micropositioner use the hollow mounts included in the accessory.

Material

Qty.	Cat.-no.	Designation
1	736 401	Fiber Optic Adapter
1	736 415	Fiber Micropositioner
1	736 425	Set of FSMA Optical Fibers
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
1	726 962	Function Generator 200 kHz
1	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
2	500 614	Safety Connection Lead 25 cm, black
2	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Carrying out the experiment



Preliminary settings

- Set the function generator to: *f* = 1 kHz, use TTL (SYNC)
- Set the fiber optic adapter to: Mode = norm. Receiver output: Analog

Determining the numerical aperture of the PMMA fiber

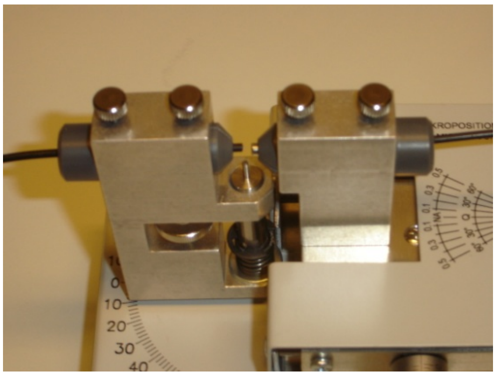
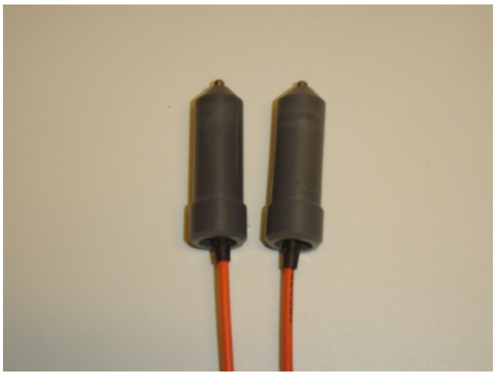
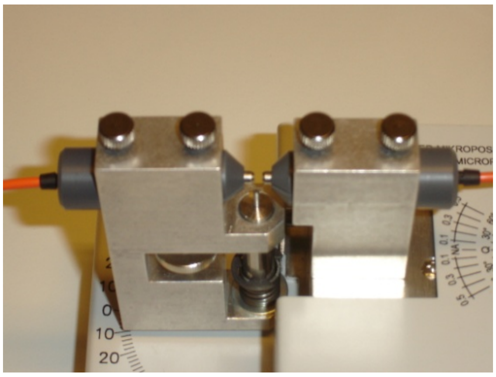
- Use LED 665 nm.
- The measurement of the NA of PMMA needs:
  1 fiber with two FSMA plugs (5 m) from 736 425 and
  1 fiber section with only one FSMA plug from 736 415
- Insert the connector-free end of the PMMA fiber (accessory of 736 415) into the narrow fiber mount of the micropositioner (736 415), see figures on the next page.
- Insert the PMMA fiber with FSMA plug into the wide fiber mount of the micropositioner (736 415). **Note:** it is practical to place the micropositioner on the desk!
- Load the CASSY Lab 2 example NumAp.labx.
- Align the fiber ends symmetrically to the axis of rotation. The space between the fiber ends amounts to approx. 2 mm.
- Set the angular positioner to 0°.
- Use the Y-manipulator on 736 415 to calibrate to minimum lateral offset, recognizable when the maximum output signal V_R is measured.
- Proceed in the same fashion to calibrate the Z-axis for the height adjustment using the thumb screw.
- Enhance the longitudinal separation X (gap) or calibrate by shifting the slider in the CASSY instrument *Calibration* the attenuation to 0 dB.
- Press the button *F9* to take the first measurement.

- Enhance the angle of the fiber axes by 2° (direction is arbitrary, above or below).
- Again maximize the received voltage V_R with Y-manipulator.
- Press *F9* again.
- Continue your measurements until you reach the maximum angular position.
- **Note:** the angular position indicated on the scale is only 50% of the incident angle on the fiber's surface.
- Add a horizontal reference line at -15 dB (ALT+ H). Place a vertical line (ALT+ V) at the intersection point between this reference line and the curve.
- Read off the angle.
- Set the slider in CASSY instrument "*Aperture Angle* Θ_A" to this determined angle.
- Read the numerical aperture in the instrument NA and note the results into the table.

Determining the numerical aperture of the HCS fiber

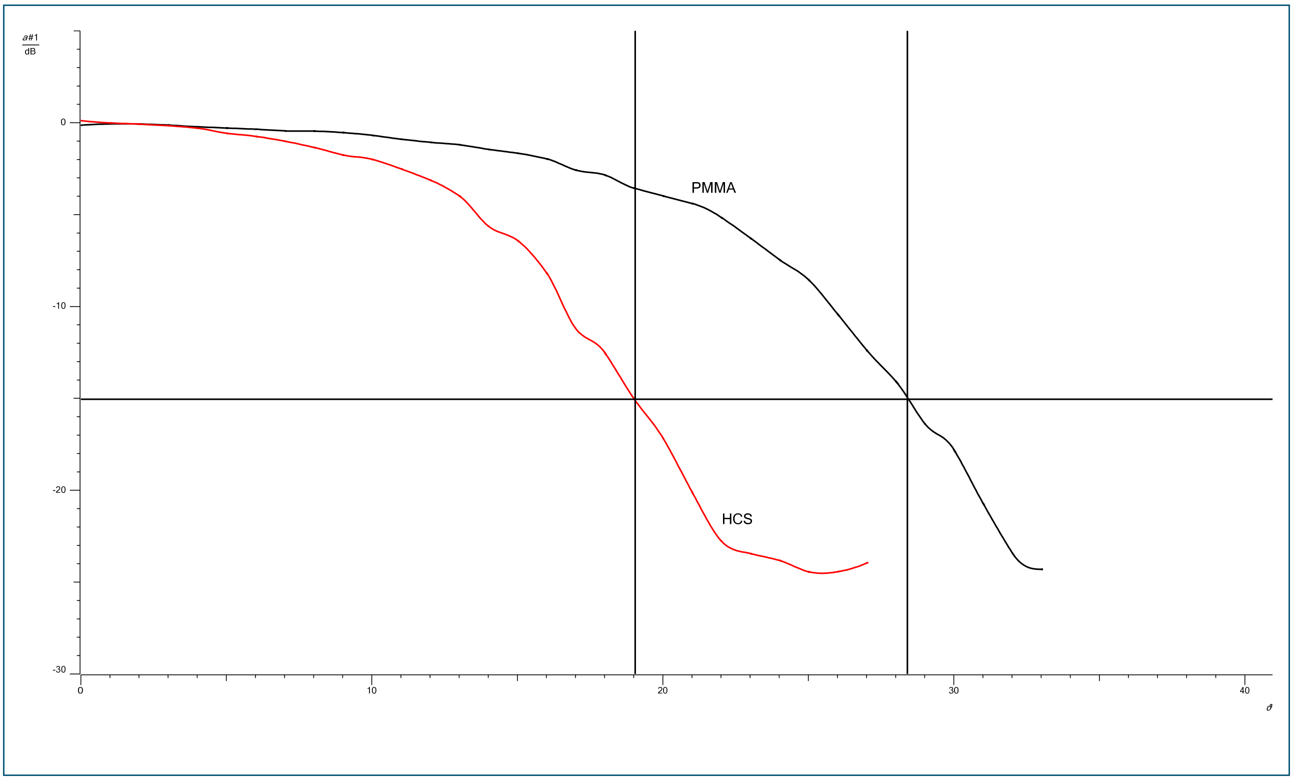
- Use LED 820 nm.
- Use the two HCS cables from 736 425 (5 m and 50 m).
- Use the hollow FSMA fiber mounts of the micropositioner.
- Maintain a small air-gap between the connectors so as to avoid pinching while turning.
- Open *Settings*.
- Activate *Add new measurement*.
- Proceed as before with PMMA and 665 nm.
- If necessary, open the CASSY instruments (*cal, a,* V_R, Θ_A).
- Enter your results into the table.
- Discuss your results.

Fiber	Acceptance Angle	Numerical Aperture
PMMA		
HCS		

	Left: PMMA fiber without FSMA connector in the narrow fiber mount. Right: PMMA fiber with FSMA connector in the wide fiber mount.
	PMMA fibers with / without FSMA connector in the fiber micropositioner.
	HCS fibers in the wide fiber mounts.
	HCS fibers with FSMA connector in the fiber micropositioner.

Results

Determining the numerical aperture of multimode fibers



Numerical aperture of the PMMA and HCS fibers

Black: Determination of the NA for PMMA 980/1000: Θ_A = 29°, NA = 0.49
Red: Determination of the NA for HCS 200/230: Θ_A = 18°, NA = 0.31.

Fiber	Acceptance Angle	Numerical Aperture
PMMA	29 (28)	NA = 0.49 (0.46)
HCS	18 (22)	NA = 0.31 (0.37)

Note: Values in brackets () are official values.

Interpretation

The determination of the NA and acceptance angle according to the method described above gives results close to the manufacturer's data.

Worksheets

Questions

1. Optical transmission in fiber optic fibers takes place according to which laws?

2. The laws of beam optics apply under what conditions?

3. What limits the data transmission rate of LEDs?

4. What possibilities exist to increase the data rate?

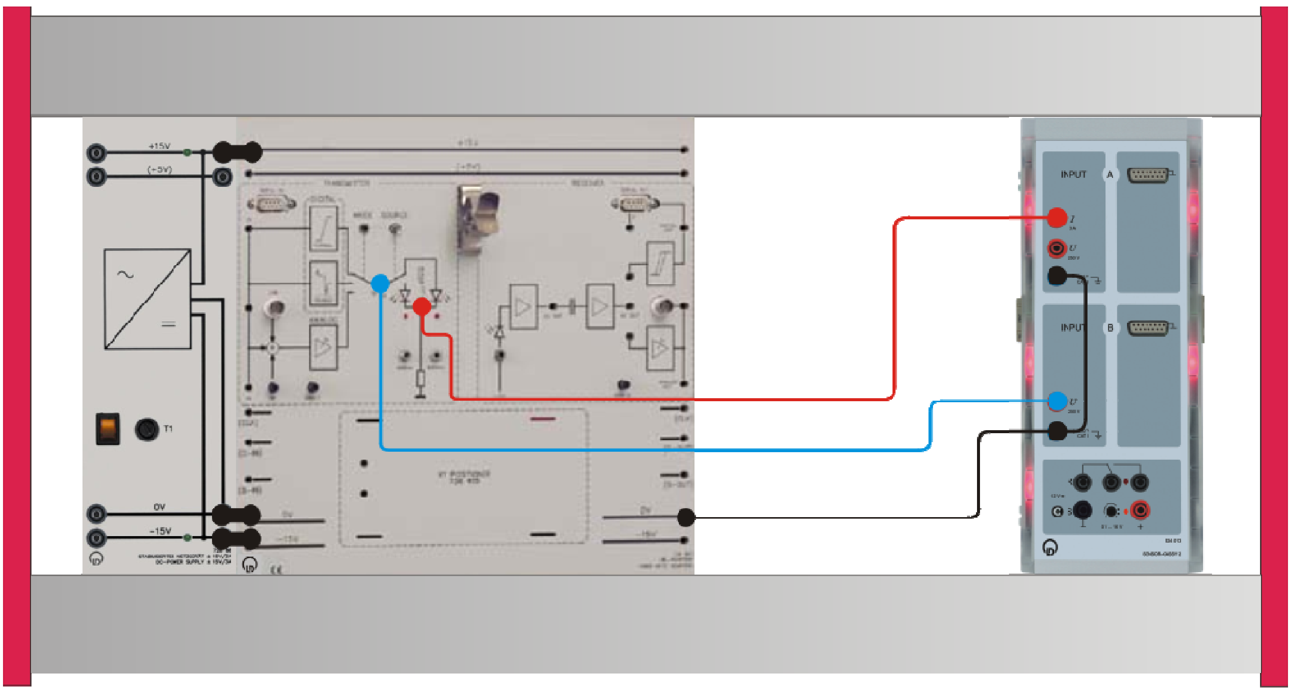
5. How is the FSMA connector constructed and what kind of features does it have?

Characteristics of the LEDs

Material

Qty.	Cat.-no.	Designation
1	736 401	Fiber Optic Adapter
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
1	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
2	500 614	Safety Connection Lead 25 cm, black
4	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Carrying out the experiment



Presettings

- Fiber optic adapter
  OP: left limit
  MODE: ANALOG
  SOURCE: 665 nm.

- Set up the experiment as shown.
- Load the CASSY Lab 2 example LED_Char.labs.
- Select the representation *IV-Characteristic*.
- Start the measurement by pressing *F9*.
- Open the instruments V_F and I_F.
- Increase the forward voltage U_F by slowly turning the potentiometer *OP* to the right. In the range where the current increases abruptly slow down accordingly.
- **Note:** The forward voltage U_F and current I_F are measured at the sockets V_{LED} or I_{LED} x 10 Ω. The forward current I_F is converted into a voltage across the 10 Ω resistor.
- Stop the measurement by pressing *F9*.
- Repeat the measurement for 820 nm.
- Sketch the current-voltage characteristics (*IV*) of both LEDs commonly in one diagram.
- Determine the parameters of the LEDs with CASSY Lab.
- Make a right click into the graphic area and select: *Fit Function Best-fit / Straight Line*. The threshold voltage U_S is obtained from the point where the tangent intersects the voltage axis. The differential resistance r_F of the LEDs is obtained from inverse value of the slope.
- Interpret the results.
- Display the graph of the electrical input power P_1 absorbed for both LEDs, by clicking on the representation *PI-Characteristic. Note:* $P_1 = I_F \times U_F$

LED	**665 nm**	**820 nm**
Threshold voltage V_S		
Differential resistance r_F		

Variant

- Measuring of the optical power P_2 as a function of the forward current I_F of the LEDs and discussing the electro-optical efficiency.

Results

IV-Characteristic of the LEDs (665 nm/820 nm)

LED	**665 nm**	**820 nm**
Threshold voltage V_S		
Differential resistance r_F		

PI-Characteristic of the LEDs (620 nm/820 nm)

Observations

On the displacement of the two characteristics

Attenuation in optical fibers

Measurement methods to determine attenuation

Attenuations can be measured either according to the throughput method or according to the principle of pulse reflectometry. Throughput measurements require access to both ends of the cable (normally not possible for installed cables). The pulse reflectometry only needs measurements on one end of the cable but also requires considerably more measurement equipment. One standard throughput measurement is performed according to the cutback method. Here the optical power P_2 is measured at one end of a known cable length. Then the cable is cut back to a few meters in length and the transmitted optical power is determined again. This method is used to keep the launch conditions the same. This advantage is offset by the disadvantage that the measurements are not without damage. Every measurement irreversibly means the loss of a section of fiber. After a finite number of measurements the fiber becomes too short. This procedure is too expensive for student training. For the purpose of experimentation attenuation measurements are performed as throughput measurements on optical fibers of different length, which are equipped with plug connectors on both ends. A typical parameter for an optical fiber is the attenuation *a* per unit length (e.g. km). In the experiment the attenuation is measured for a difference length Δl = 45 m (a_{45}). Thus the attenuation *a* per km has to be corrected by the factor 1000/45:

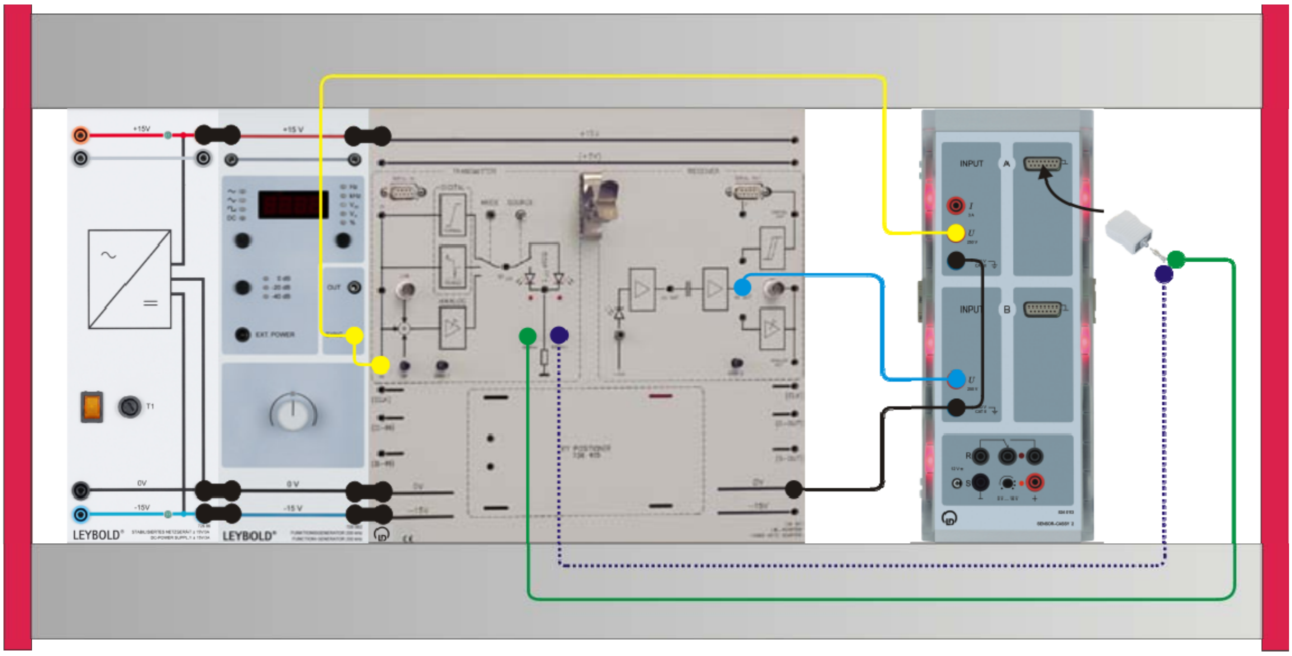
$$a = \frac{1000}{45} \cdot a_{45}\ dBkm^{-1} \qquad (3.1)$$

Material

Qty.	Cat.-no.	Designation
1	736 401	Fiber Optic Adapter
1	736 425	Set of FSMA Optical Fibers
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
1	726 962	Function Generator 200 kHz
1	524 0512	Optical Power Sensor S
1	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
1	500 592	Set of 10 Safety Bridging Plugs with Tap, black
2	500 614	Safety Connection Lead 25 cm, black
4	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Carrying out the experiment

Attenuation per unit length



- Set up the experiment
- Set the function generator to: 2 kHz, use the TTL out (Sync).
- Set the fiber optic adaptor to: Mode = norm, Source = 665 nm.

PMMA

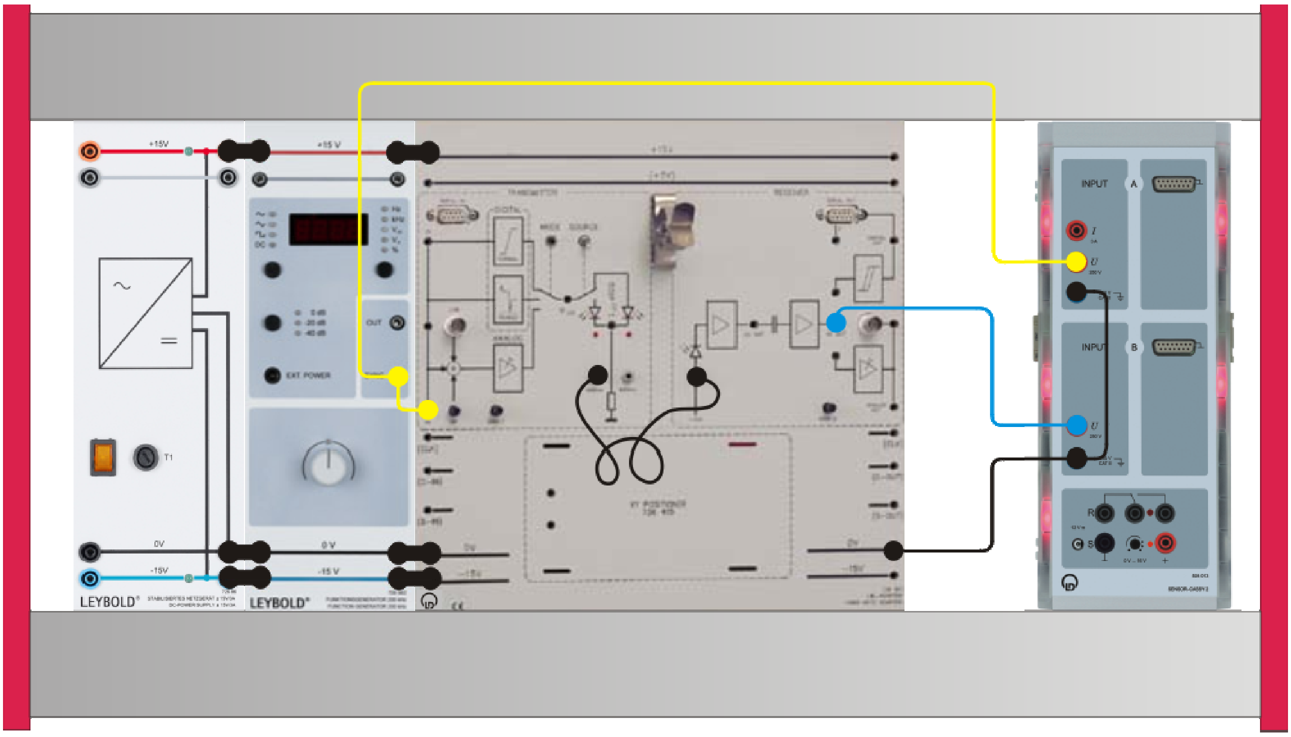
- Connect the PMMA fiber (l = 5 m) to the LED 665 nm and to the optical power sensor.
- Load the CASSY Lab example FiberLoss.labs.
- Calibrate the optical power sensor. For that make a right click into the instrument optical power PA1 / Settings → 0 ←.
- Close settings.
- Replace the PMMA fiber (l = 5 m) by the l = 50 m.
- Read the attenuation on the instrument *Attenuation 45*.
- Enter the value into the table.
- Repeat the experiment with PMMA-fibers for 820 nm.

HCS

- Connect the HCS fiber (l = 5 m) to 820 nm and to the optical power sensor.
- Calibrate the optical power sensor. For that make a right click into the instrument optical power PA1 -> Settings → 0 ←.
- Close settings
- Replace the HCS-fiber (l = 5 m) by the l = 50 m
- Read the attenuation on the instrument *Attenuation 45.*
- Enter the value of the attenuation into the table.
- Repeat the experiment with HCS-fibers for 665 nm.

	Attenuation	
	PMMA	**HCS**
665 nm		
820 nm		

Display of the received signals



- Set up the experiment
- Set the function generator to: 2 kHz, use the TTL out (Sync).
- Set the fiber optic adaptor to: Mode = norm, Source = 665 nm.

PMMA

- Connect the LED 665 nm and the photo detector (TIC) with the PMMA-fiber l = 5 m.
- Load the CASSY Lab 2 example Attenuation.labs.
- Start the measurement by pressing *F9*.
- Repeat the measurement for the PMMA-fiber l = 50 m.
- Sketch both measurements within a single diagram.
- Repeat the measurements for the LED 820 nm.
- Give an interpretation.

HCS

- Repeat the experiment for the HCS-Fibers with l = 5/50 m.
- Again use LED 665 nm and LED 820 nm.

Results

Attenuation in PMMA and HCS per unit length

	Attenuation	
	PMMA	**HCS**
665 nm	349.8 dB/km	13.2 dB/km
820 nm	Not determined > 500 dB/km	dB/km

Display of the received signals using PMMA-fibers

PMMA **λ = 665 nm**

Red: Modulating signal unipolar, TTL, 2 kHz
Black: PMMA fiber l = 5 m, bipolar, approx. 3.7 V_{pp}, inverse polarity
Blue: PMMA fiber l = 50 m, bipolar, approx. 0.1 V_{pp}, inverse polarity

PMMA **λ = 820 nm**

Red: Modulating signal unipolar, TTL, 2 kHz
Black: PMMA fiber l = 5 m, bipolar, approx. 0.2 V_{pp}, inverse polarity
Blue: PMMA fiber l = 50 m, bipolar, no signal detectable (approx. 0 V_{pp})

HCS **λ = 820 nm**

Red: Modulating signal unipolar, TTL, 2 kHz
Black: HCSA fiber l = 5 m, bipolar, approx. 5.8 V_{pp}, inverse polarity, saturation effect
Blue: HCS fiber l = 50 m, bipolar, approx. 5.4 V_{pp}, inverse polarity, strong signal nearly saturated.

The cable lengths are too short to give a strong attenuation.

HCS **λ = 665 nm**

Red: Modulating signal unipolar, TTL, 2 kHz
Black: HCS fiber l = 5 m, bipolar, approx. 2.5 V_{pp}, inverse polarity
Blue: HCS fiber l = 50 m, bipolar, approx. 2.2 V_{pp}, nearly no difference than the output at l = 5 m.

Interpretation

Notes

- With exceeding optical power levels, transmission disturbances can arise.
- These disturbances are stronger for small cable lengths (5 m) and in peaked mode.
- In normal operating mode the light power of the LEDs is smaller than in peaked power mode.
- Phase shift between the modulating signal and the receiving signal arises only at AC out.

Digital transmission methods

In practice, distortions caused by bad or faulty connections can be introduced into the transmission link. The effect of these kinds of distortions is a drop of optical power at the photo diode resulting in the attendant problems involving threshold value recognition by the receiver. The statistical emergence of bit errors depends on the signal-to-noise ratio SNR at the optical receiver as shown in Fig. 4.1.

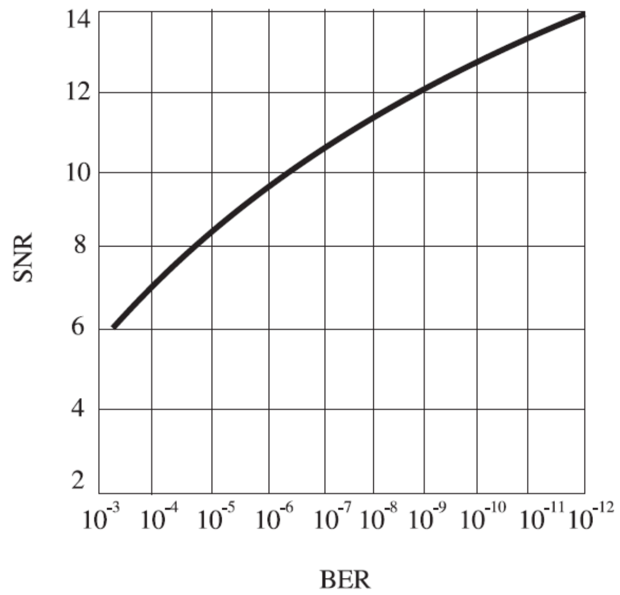
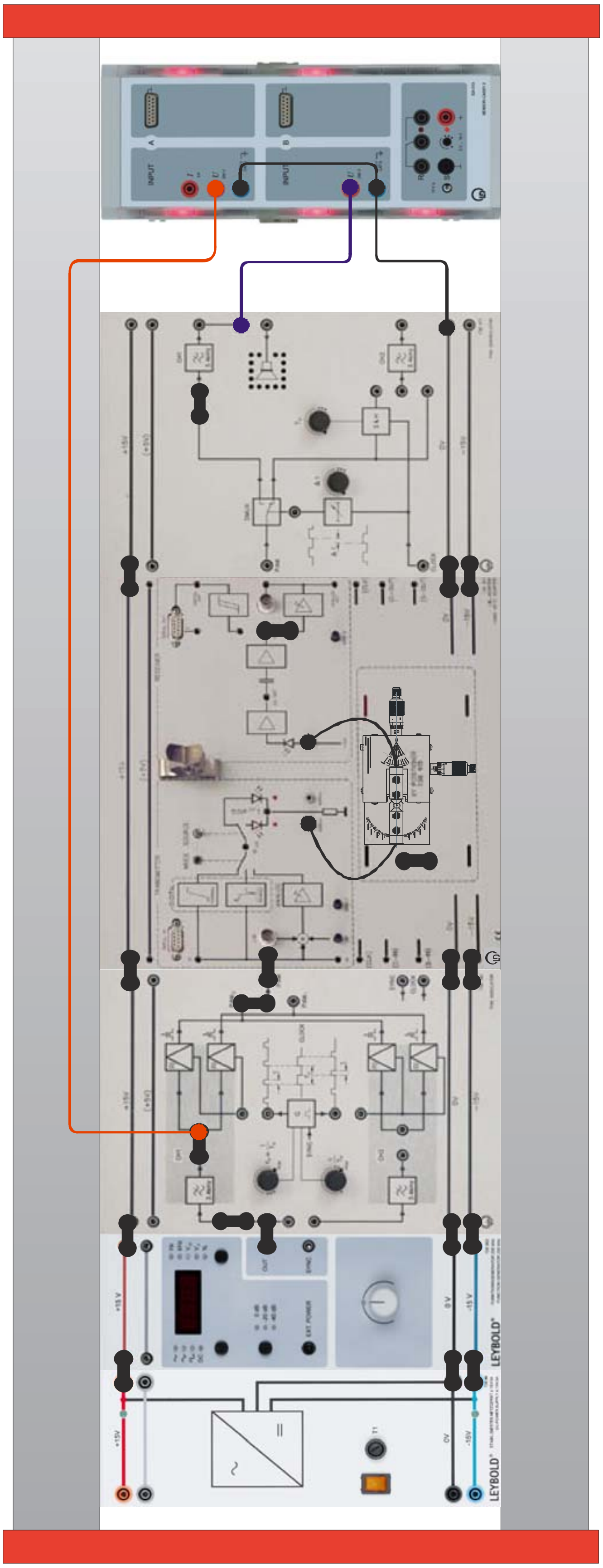


Fig. 4.1: Dependency of the bit error rate BER on the SNR

Material

Qty.	Cat.-no.	Designation
1	736 061	PAM Modulator
1	736 071	PAM Demodulator
1	736 101	PCM Modulator
1	736 111	PCM Demodulator
1	736 401	Fiber Optic Adapter
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
2	726 962	Function Generator 200 kHz
4	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
1	500 592	Set of 10 Safety Bridging Plugs with Tap, black
2	500 614	Safety Connection Lead 25 cm, black
4	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Transmission of PAM via fiber micropositioner

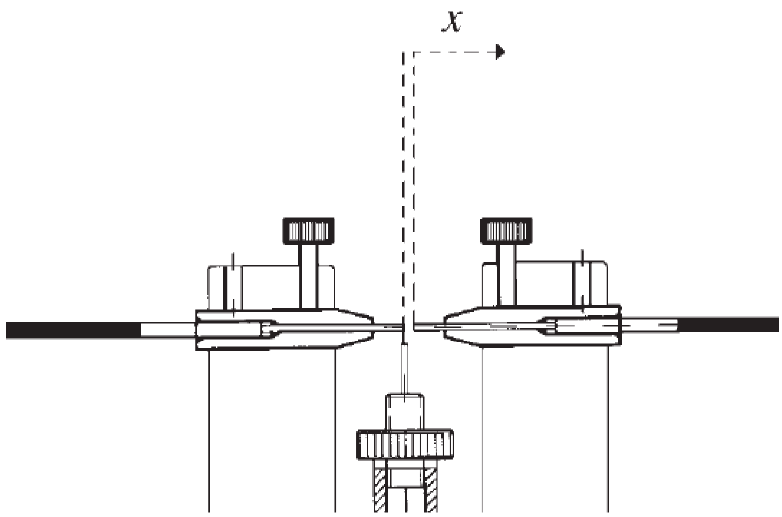


- Set up the experiment as shown.
- Function generator: sine, 500 Hz, 10 V_{pp}.
- Use fiber sections equipped with FSMA connectors on one end which have been included with the fiber micropositioner, see detailed sketch.

Calibration

- Set the fiber optic adaptor to: Source = 665 nm. Mode = analog.
- Set the PAM Modulator to: τ/T_P → PCM (maximum right), f_P → maximum left)
- Load the CASSY Lab 2 example PAMCal.labs.
- Start the measurement by pressing *F9*.
- Display the receiving signal at Analog Out of the fiber optic adapter.
- Adjust OP, GAIN 1, GAIN 2 until the modulating signal at the output of the channel filter CH 1 is coincident with the output signal at Analog OUT.

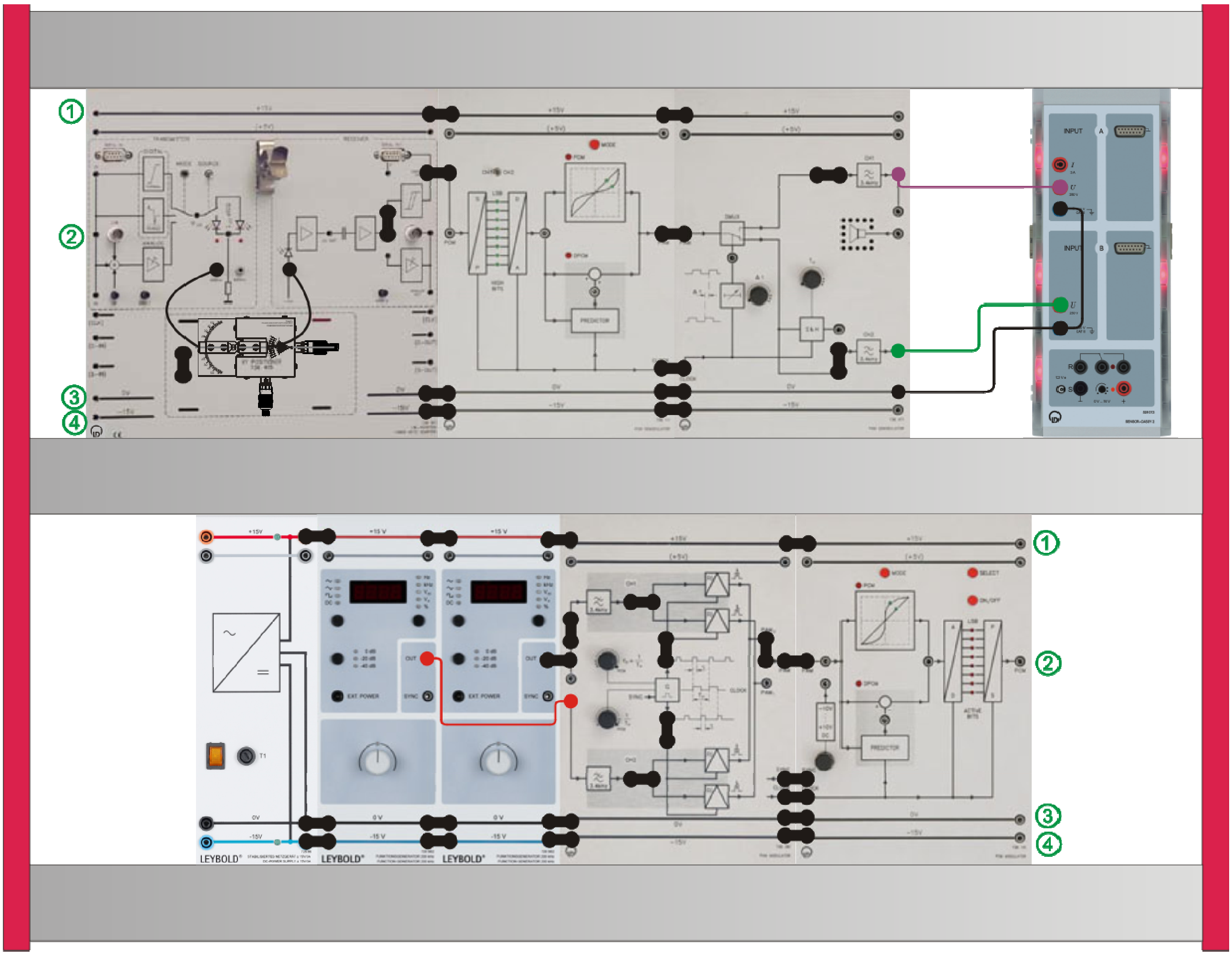
- Fiber micropositioner: Set X-manipulator to zero.
- If necessary adjust the fiber ends (X) in the holder, until you obtain again coincidence between the modulating signal and the PAM signal.
- Stop the calibration measurement by pressing *F9*.



Detailed sketch on how to produce transmission distortions with the fiber micropositioner

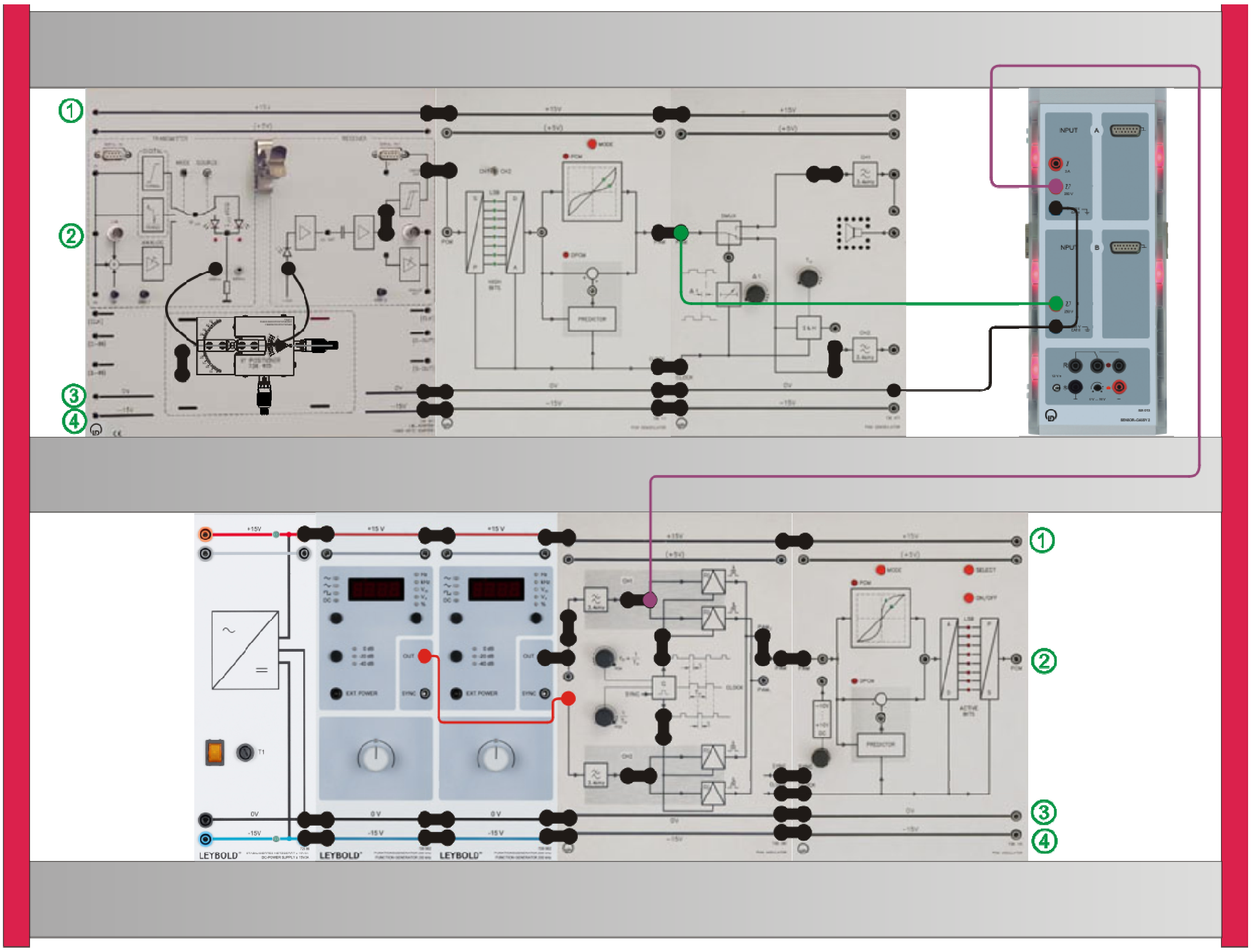
- Connect channel B to the output of the PAM demodulator as shown.
- Load the CASSY Lab 2 example PAMModDem.labs.
- Start the measurement by pressing *F9*.
- Sketch the modulating signal and the demodulated signal for an air gap x = 0 mm at the micropositioner.
- Repeat the measurement for a longitudinal setting of 1.0 mm respectively 2.0 mm.
- For that turn the X-micrometer of the fiber micropositioner to 1.0/2.0 mm. **Note:** 1 mm means 2 turns of the micrometer screw!
- Discuss your results.

Transmission of PCM via fiber micropositioner



- Set up the experiment as shown.
- Function generator 1: triangular, 250 Hz, 15 V_{pp}.
- Function generator 2: sine, 500 Hz, 10 V_{pp}.
- Set the PAM Modulator to: τ/T_P → PCM (maximum right), f_P → PCM (maximum right)
- Fiber optic adaptor: Mode = normal, source = 665 nm. **Note:** Set a bridging plug from AC-out to the comparator. Use Digital Out.
- Fiber micropositioner: Set X-manipulator to zero.
- Load the CASSY Lab 2 example PAMModDem.labs.
- Start the measurement by pressing *F9*.
- Increase the longitudinal separation X of the fibers. If necessary add angular misalignment until the PCM transmission gets disturbed.
- Sketch the demodulated signals of CH 1 and CH 2 at the outputs of the PAM demodulator.
- Give an interpretation of the results.

Time division multiplex signals



- Set up the experiment as shown.
- Function generator 1: triangular, 250 Hz, 15 V_{pp}.
- Function generator 2: sine, 500 Hz, 10 V_{pp}.
- Set the PAM Modulator to: τ/T_P → PCM (maximum right), f_P → PCM (maximum right)
- Fiber optic adaptor: Mode = normal, source = 665 nm
- Set the fiber micropositioner to the start conditions for undisturbed PCM transfer. Not critical!
- Load the CASSY Lab 2 example PCMTDM.labs.
- Start the measurement by pressing *F9*.
- Give an interpretation of the results.

Results

Transmission of PAM via fiber micropositioner

Calibration

Calibration for PAM with the fiber micropositioner

Black: Modulating signal at the PAM modulator

Red: PAM; signal at Analog out of the fiber optic adapter

PAM-Transmission X = 0.00 mm

Digital transmission of PAM with the fiber micropositioner. Modulating & demodulating signal

Black: Modulated signal ca. A_M = 10.6 V_{pp}

Red: Demodulated signal, ca. A_D = 5.3 V_{pp}.

Interpretation

PAM-Transmission X = 1.0 mm

Digital transmission of PAM with the fiber micropositioner.

Black: Modulated signal ca. $A_M = 10.6\ V_{pp}$
Red: Demodulated signal, ca. $A_D = 3.6\ V_{pp}$.

Observation

PAM-Transmission X = 2.0 mm

Digital transmission of PAM with the fiber micropositioner

Black: Modulated signal ca. A_M = 10.6 V_{pp}
Red: Demodulated signal, ca. A_D = 1.9 V_{pp}.

Observation

PCM-Transmission X = 0.0 mm

Digital transmission of PCM with the fiber micropositioner

Black: Demodulated triangular signal
Red: Demodulated sinusoidal signal

Observations

PCM-Transmission, disturbed

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Digital transmission of PCM with the fiber micropositioner

Black: Modulated signal, channel 1. Totally distorted

Red: Demodulated signal, channel 2.Totally distorted

Interpretation

Time division multiplex signals

Digital transmission of PCM with the fiber micropositioner. Modulating & time division multiplexing signals.

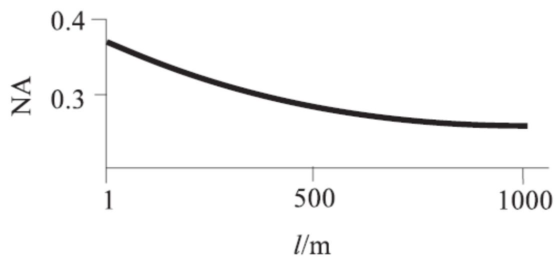
Black: Modulating signal of channel 1
Red: Time division signal for two channels. CH 1: sine, CH 2: triangular

Observations

Determining the numerical aperture

Fundamentals

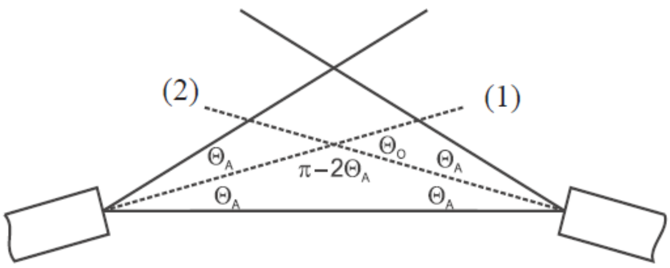
The numerical aperture (NA) is an important parameter in fiber optics. A high NA results in great coupling effectiveness, i.e. incidenting light can easily be coupled into the fiber. Also the losses resulting from bends decrease with increasing numerical aperture. In HCS fibers the numerical aperture is a function of the fiber length. In the case of short fiber lengths a portion of the light is also propagated in the cladding or in higher modes. Due to stronger attenuation for these modes the numerical aperture declines with increasing fiber length.



The numerical aperture (NA) of an HCS fiber as a function of the fiber length

The determination of the numerical aperture with the aid of the fiber micropositioner (736 415), is a simplified method based on the measurement of the angle θ_O of the optical axis of two fibers. The axe angle is two times the incident angle on the fiber surface. Because open fiber ends do not radiate equally into all directions (no omnidirectional radiation pattern), the acceptance angle Θ_{AC} is reached gradually, without a sharp transition from radiation to non-radiation.

$$\Theta_0 = 2\Theta_A = 2 \cdot \arcsin NA \qquad (5.1)$$



How to measure the acceptance angle Θ_A. (1), (2): Longitudinal axis of the fibers encompass the optical axis angle θ_O

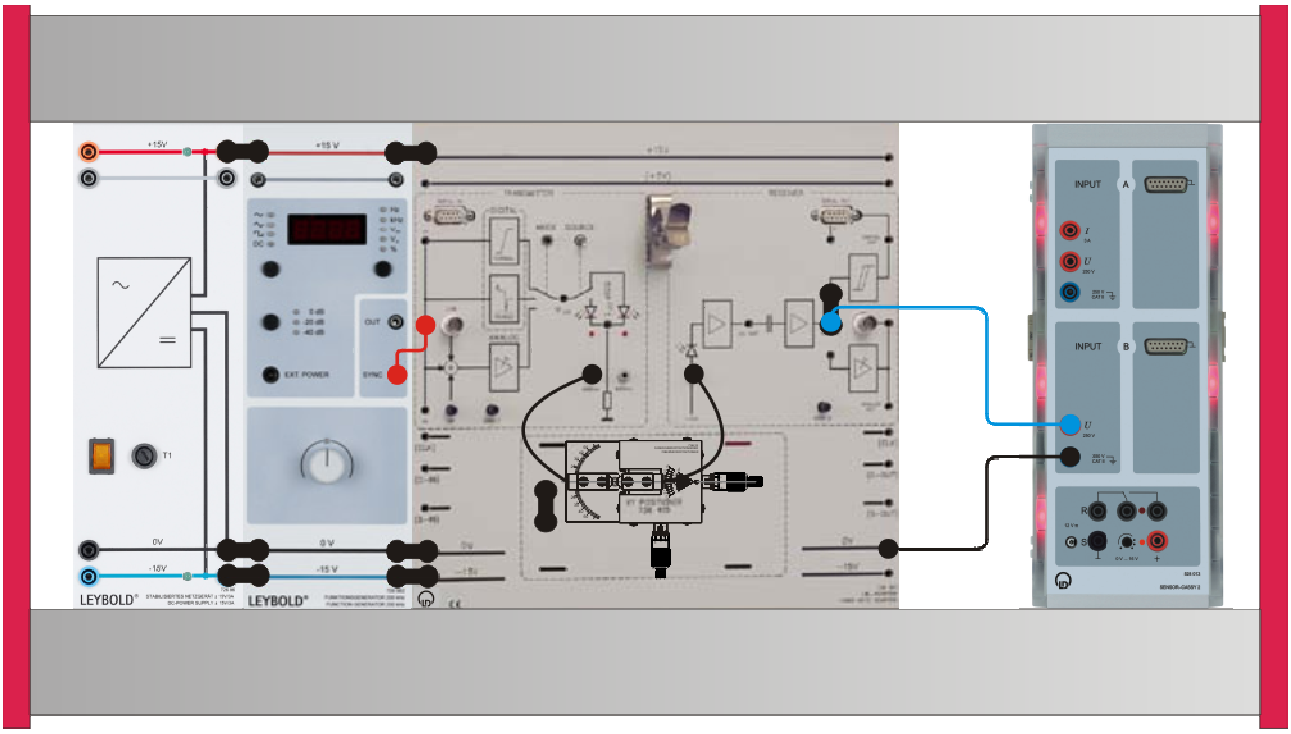
Notes

- This experiment requires some practical experiences with regard to a proper alignment of the angular positioner and the lateral offset.
- The acceptance angle θ_A is determined at the intersection point with -15 dB below the reference intensity at θ_O = 0 dB.
- Although sometimes the intersection point is measured at a threshold of -20 dB (this gives a somewhat greater acceptance angle and higher NA) there is no significant difference in the procedure.
- The acceptance angle θ_A can be estimated directly from the angular scale of the micropositioner.
- For fixing fibers with FSMA-connectors to the fiber micropositioner use the hollow mounts included in the accessory.

Material

Qty.	Cat.-no.	Designation
1	736 401	Fiber Optic Adapter
1	736 415	Fiber Micropositioner
1	736 425	Set of FSMA Optical Fibers
1	726 09	Panel Frame T130, Two Level
1	726 86	DC-Power Supply ± 15 V/ 3 A
1	726 962	Function Generator 200 kHz
1	500 59	Set of 10 Safety Bridging Plugs, black
1	500 614	Safety Connection Lead 25 cm, black
2	500 614	Safety Connection Lead 25 cm, black
2	500 644	Safety Connection Lead 100 cm, black
1	524 013S	Sensor-CASSY 2 - Starter

Carrying out the experiment



Preliminary settings

- Set the function generator to: *f* = 1 kHz, use TTL (SYNC)
- Set the fiber optic adapter to: Mode = norm. Receiver output: Analog

Determining the numerical aperture of the PMMA fiber

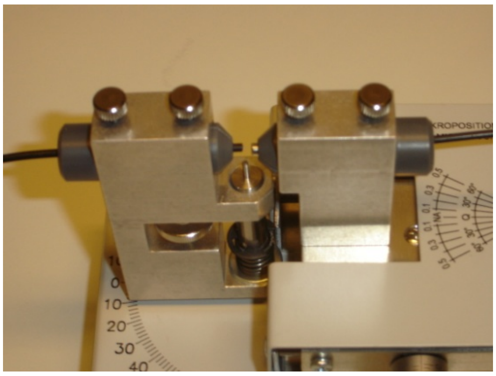
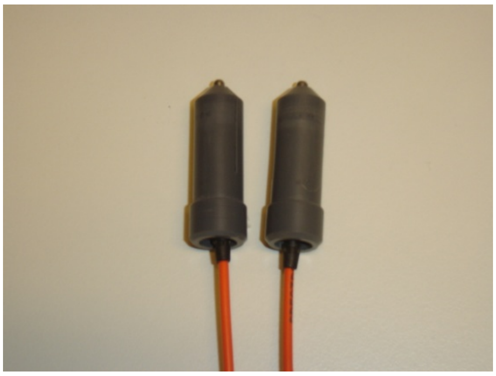
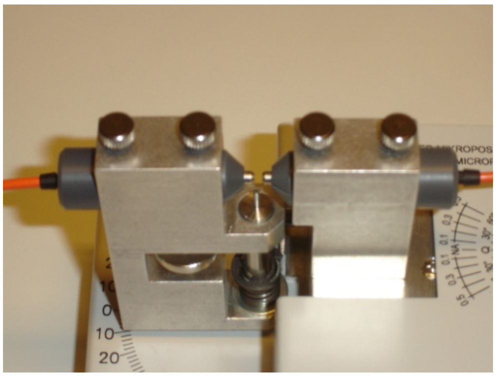
- Use LED 665 nm.
- The measurement of the NA of PMMA needs:
  1 fiber with two FSMA plugs (5 m) from 736 425 and
  1 fiber section with only one FSMA plug from 736 415
- Insert the connector-free end of the PMMA fiber (accessory of 736 415) into the narrow fiber mount of the micropositioner (736 415), see figures on the next page.
- Insert the PMMA fiber with FSMA plug into the wide fiber mount of the micropositioner (736 415). **Note:** it is practical to place the micropositioner on the desk!
- Load the CASSY Lab 2 example NumAp.labs.
- Align the fiber ends symmetrically to the axis of rotation. The space between the fiber ends amounts to approx. 2 mm.
- Set the angular positioner to 0°.
- Use the Y-manipulator on 736 415 to calibrate to minimum lateral offset, recognizable when the maximum output signal V_R is measured.
- Proceed in the same fashion to calibrate the Z-axis for the height adjustment using the thumb screw.
- Enhance the longitudinal separation X (gap) or calibrate by shifting the slider in the CASSY instrument *Calibration* the attenuation to 0 dB.
- Press the button *F9* to take the first measurement.

- Enhance the angle of the fiber axes by 2° (direction is arbitrary, above or below).
- Again maximize the received voltage V_R with Y-manipulator.
- Press *F9* again.
- Continue your measurements until you reach the maximum angular position.
- **Note:** the angular position indicated on the scale is only 50% of the incident angle on the fiber's surface.
- Add a horizontal reference line at -15 dB (ALT+ H). Place a vertical line (ALT+ V) at the intersection point between this reference line and the curve.
- Read off the angle.
- Set the slider in CASSY instrument "*Aperture Angle* Θ_A" to this determined angle.
- Read the numerical aperture in the instrument NA and note the results into the table.

Determining the numerical aperture of the HCS fiber

- Use LED 820 nm.
- Use the two HCS cables from 736 425 (5 m and 50 m).
- Use the hollow FSMA fiber mounts of the micropositioner.
- Maintain a small air-gap between the connectors so as to avoid pinching while turning.
- Open *Settings*.
- Activate *Add new measurement*.
- Proceed as before with PMMA and 665 nm.
- If necessary, open the CASSY instruments (*cal, a,* V_R, Θ_A).
- Enter your results into the table.
- Discuss your results.

Fiber	Acceptance Angle	Numerical Aperture
PMMA		
HCS		

	Left: PMMA fiber without FSMA connector in the narrow fiber mount. Right: PMMA fiber with FSMA connector in the wide fiber mount.
	PMMA fibers with / without FSMA connector in the fiber micropositioner.
	HCS fibers in the wide fiber mounts.
	HCS fibers with FSMA connector in the fiber micropositioner.

Results

Determining the numerical aperture of multimode fibers

Numerical aperture of the PMMA and HCS fibers

Black: Determination of the NA for PMMA 980/1000: Θ_A = 29°, NA = 0.49
Red: Determination of the NA for HCS 200/230: Θ_A = 18°, NA = 0.31.

Fiber	Acceptance Angle	Numerical Aperture
PMMA		NA =
HCS		NA =

Note: Values in brackets () are official values.

Interpretation