T 7.2.6

T 7.2.6.1 Experiments with PMMA-Fibers 564 482

T 7.2.6

Fiber Optics

T 7.2.6.1
Experiments with PMMA-Fibers

2nd edition

Version: 17BB07PME14W010

564 482

Notes

Equipment

- Connect the fiber optic transmitter and the fiber optic receiver with the plug in power supplies.
- Insert the plug in power supply into a suitable wall outlet.
- Optical power sensor S: The display of the instruments of the optical power sensor (CASSY Lab) starts blinking under excessive illumination or with too weak light signals.
- For measurements with plug less PMMA-fibers (from the set of fiber-optic waveguides and accessories 736 421) use the loose fiber adaptor.

Use of the CASSY example files

- Copy the files included in the CD (text as *.pdf and measurement files as *.labx) in the same subdirectory, e.g. C:\FiberOptics_T7261.
- Install the CASSY Lab Software on your PC.
- By clicking “Load the CASSY Lab example”, a special measurement file is loaded, customized for the experiment. If the automatic start fails on your PC, you have to start the file *name.slab* manually.
- Loading the measurement files requires the CASSY Lab 2.

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 measurement interface CASSY and the software CASSY Lab are very versatile tools, they are preferred for experimentation.

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!

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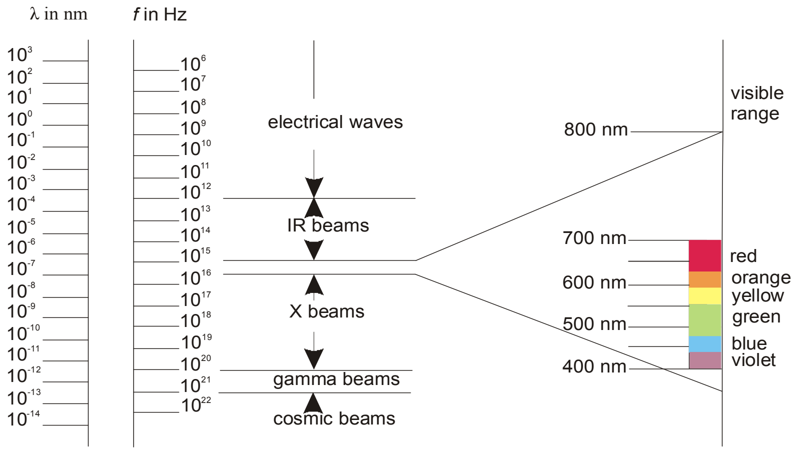
Theory

Physical principles

The electromagnetic spectrum

For the transmission of messages, the propagation of electromagnetic waves in a transmission medium is of fundamental importance. The medium does not have to be a metalic 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 short-wave cosmic beams. For optical communications technology only a very small range is suitable, namely infrared (IR) and visible (VIS), as well as the ultraviolet (UV) part of the electro-magnetic spectrum. 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 beams while the IR beams 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*:

$$\lambda = \frac{c_0}{f}$$



Where c_0 stands for: $c_0 = 3{\cdot}10^8$ 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.

Beam optics

Light propagation in a multimode optical waveguide can be explained using the laws of geometrical optics. Light serve as a simple theoretical concept (model). 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 waveguide is based on the laws of refraction and reflection. As a rule both processes occur when a beam incidents a dielectric surface. If a beam strikes the surface of two different substances with different refractive indexes *n*, then the following holds true according to the law of reflection:

$$\alpha = \alpha'$$

The angle of incidence α and angle of reflection α' are in the same plane.

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2}$$

The ratio of light velocity c_0 in 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.

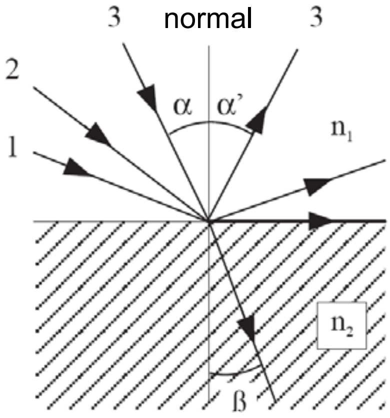
$$c = \frac{c_0}{n}$$

Using the equation we obtain:

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1}$$

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. 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:

$$\sin\alpha_c = \frac{n_2}{n_1}$$



Reflection and refraction

Thus, if the angle of incidence surpasses the critical angle α_c, no refraction can occur and the beams are totally reflected at the surface. This phenomenon is called total reflection. It only takes place during the transition from an optically denser medium to an optically less dense one.

Fiber optic telecommunications systems

Design of optical waveguides

Total reflection is exploited as the guiding mechanism in optical waveguides (multimode fibers). For this reason the optical wave guide consists of a cylindrical core and a concentric cladding surrounding. Here the refractive index n_1 in core glass is somewhat larger than that of refractive index n_2 in the glass cladding. All light beams which do not deviate more than (90°– α_c) from axial direction of the optical waveguide are guided inside the glass core. In order to launch 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 (Θ = angle between beam and fiber axis):

$$\frac{\sin\theta}{\sin(90^\circ - \alpha)} = \frac{n_1}{n_0}$$

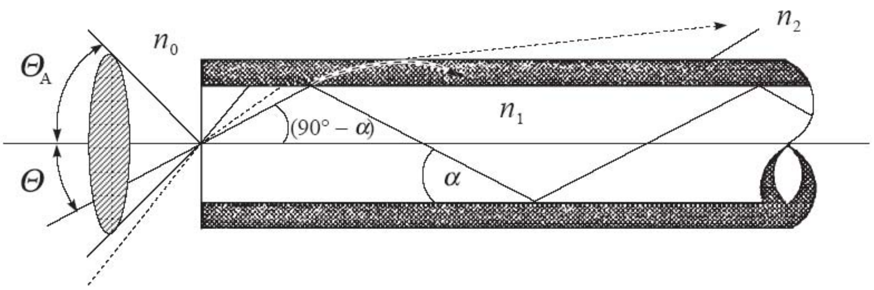
From this it follows with n_0 = 1:

$$\sin\theta = n_1 \cos\alpha = n_1 \sqrt{(1 - \sin^2\alpha)}$$

The largest coupling angle Θ_A is called the acceptance angle of the fiber optic waveguide 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 waveguide:

$$NA = \sin\theta_A = \sqrt{(n_1^2 - n_2^2)}$$

This numerical aperture *NA* B is an important quantity for coupling light into a fiber optic waveguide. The greater the numerical aperture of an optical fiber, the more light can be coupled, but this also introduce more propagation time differences between higher order modes.



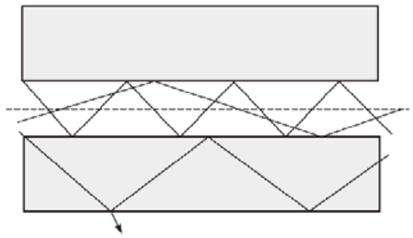
Light guided through a fiber optic waveguide

Fiber optic profiles

If we consider the refractive index *n* of a fiber optic waveguide 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 (SI)
- Graded index profile (GI)

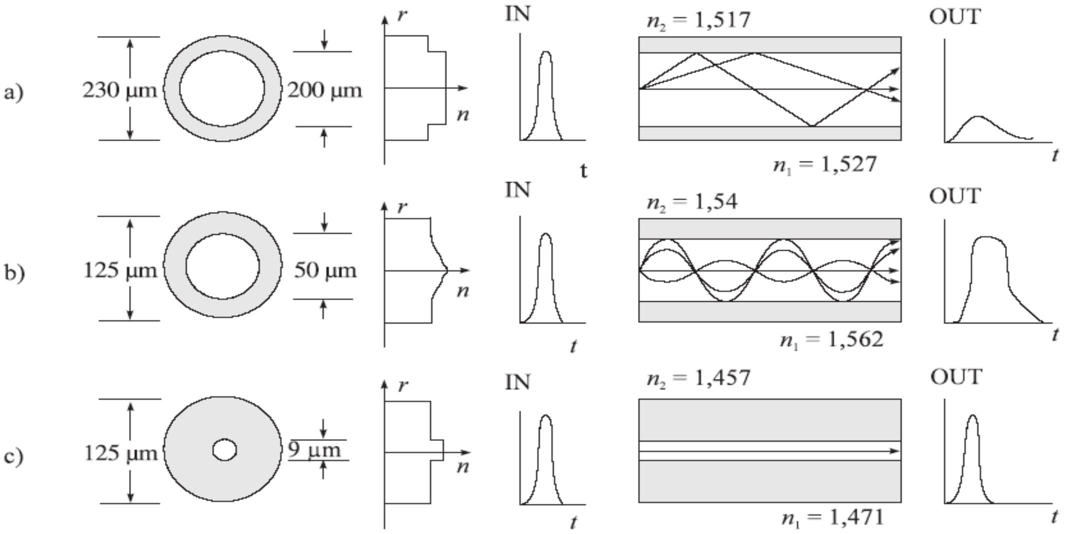
The step-index profile is characterized by a constant refractive index n_1 within the core and a sharp drop to n_2 $(n_1 > n_2)$ at the boundary between the core and cladding.



Mode distribution in a step index fiber

The figure shows that beams guided in a flatter fashion travel a shorter distance than the ones traveling at a steep angle because the latter types are reflected more frequently. This is referred to as modes of higher order (multiple zigzag course) and accordingly modes of a lower order (few reflections). Modes are possible propagation paths in a fiber optic waveguide. The existence of mode of various orders leads to complications in signal transmission. A light pulse of short duration may be 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 step index fiber is not suited for the transmission of broad band signals. The graded-index profile provides assistance here. In contrast to the step-index profile the light beams in a fiber optic waveguide do not propagate in zigzag fashion. The refraction index profile of a graded index fiber changes continuously over the radius of the fiber. The guiding mechanism of the graded index 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 beams are constantly subjected to refraction. The propagation direction is constantly changing running in wavelike paths along the axis of the fiber. Steep beams oscillating around the axis always have farther to travel than the light beams traveling along the axis. However, due to the lower refractive index outside the axis of the fiber these beams travel at faster speed, through which the longer distance is made up for in time. As a result, the differences in propagation time for the individual beams disappear almost completely. Modal dispersion is only slight. However 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 µm – 10 µm. Only one single mode can propagate along the core thus eliminating the possibility of any propagation time difference (no modal dispersion). The following figure provides an overview concerning the dimensions, refractive index profiles and some additional characteristic variables.

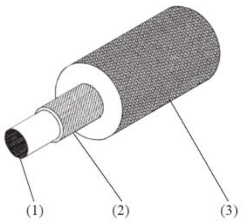
Common types of fiber optic waveguides



a:	step index (SI)	multimode	diameter core/cladding	230/200
b:	graded index (GI)	multimode	diameter core/cladding	50/125
c:	step index (SI)	monomode	diameter core/cladding	9/125

Fiber production, material selection

Plastic and silica glass have gradually become predominant for the production of fiber optic waveguides. So-called all plastic waveguides are used for simple communication systems. The most common fiber type consists of an approx. 970 µm thick core of poly-methyl-methaacrylat (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 left (up to approx. 100 m). The figure shows the schematic design of a PMMA fiber. The *NA* amounts to 0.47 which corresponds to an acceptance angle of 28°. For high traffic transmission left (e.g. cable networks and telecommunication networks operated by telephone and communications companies) 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.



Design of a PMMA fiber

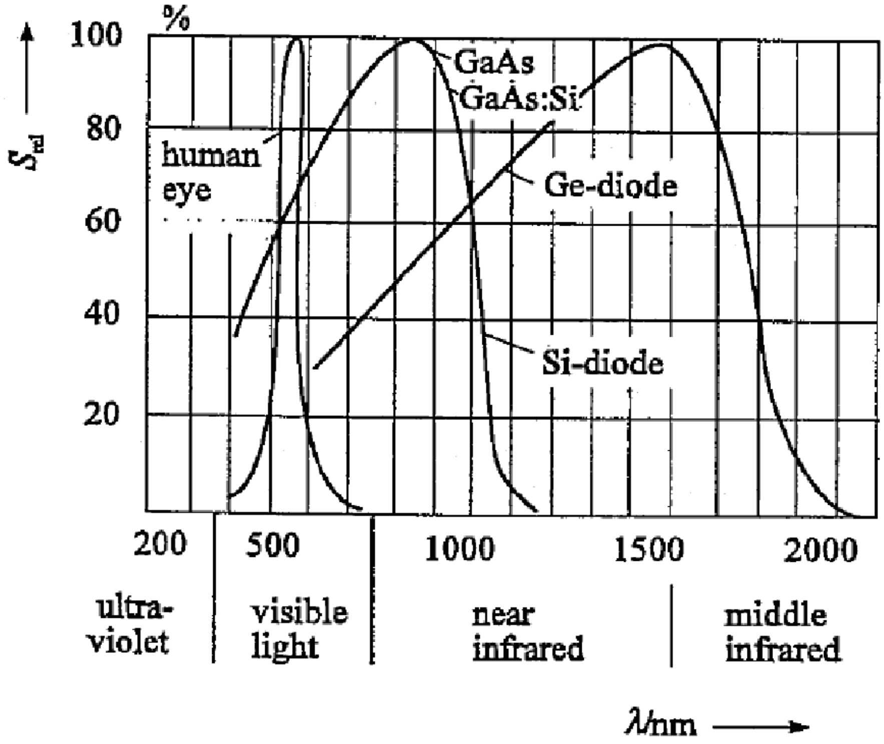
1: core, diameter:	970 µm, n_1 = 1.492
2: optical cladding:	15 µm, n_2 = 1.417
3: protective jacket, diameter:	2.2 mm

Light sources

In optical communications technology LED and solid-state lasers (LD) are primarily used as light sources. Taken from the electrical point-of-view these semiconductor light sources are considered PN diodes, which are operated in the forward direction. The effect of spontaneous recombination is exploited in LED sources.

Detectors

The opto-electrical conversion brought about by the absorption of the light beam takes place in the photodiode. In actual practice the spectral sensitivity S_{rel} is important. This indicates which current Ip is obtained at the photodiode for prespecified, incident light power P_2. Typical values for silicon diodes for a wavelength of 850 nm are at about S_{rel} = 0,5 A/W. The figure 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.



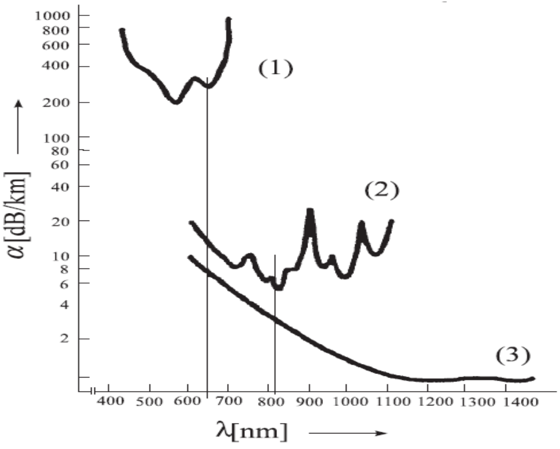
Attenuation

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 connectors
- Material attenuation of the fiber optic waveguide

The attenuation of the fiber optic waveguide depends on the wavelength, while, the attenuation of the connectors is 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 the light no longer arrives at the aperture angle opposite fiber and is thus lost for signal transmission. Material attenuation of the fiber optic waveguide is caused by:

- Light scattering
- Light absorption
- Beam losses related to the guidance of the waveguide.



Fiber optic attenuation

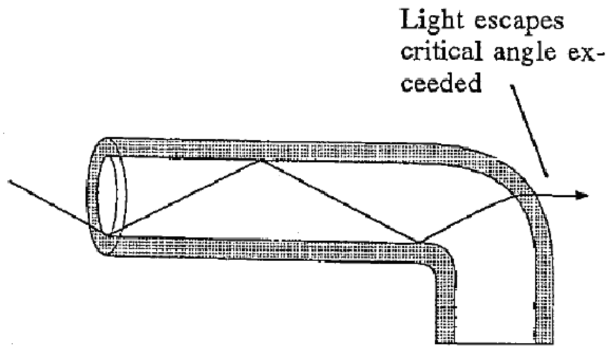
(1) APF Cable (all plastic fiber e.g. PMMA

(2) PCF plastic cladding fiber

(3) Glass fiber

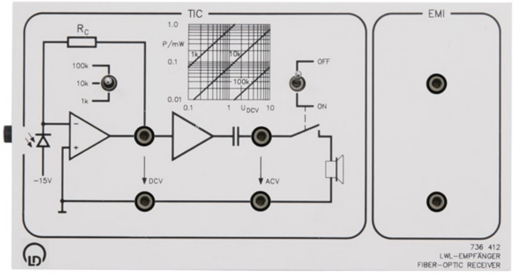
Linear scattering (Rayleigh scattering) is due to statistical fluctuations in the refractive index. These result from random molecular structures in the waveguide material. The refractive index varies in sections which are small in comparison with the wavelength of light. Absorption means the conversion of beam energy into heat when impinging on impurities (atoms or molecules). The severity of the effect depends on the wavelength and spans the entire range, from ultraviolet to infrared.

In addition to the scattering and absorption there also exists beam losses through conversion from guided 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.



However, due to the relatively high attenuation in the cladding material mantle modes are incapable of propagation even without a bent optical waveguide. 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 1300 nm (2nd window) for glass optical fibers.

Training system



736 411 Fiber optic transmitter

Three integrated, LED for experiments at various wavelengths. Potentiometer for the continuous setting of the bias voltage for recording characteristics. 4-mm sockets for the connection of the Sensor-CASSY interface. Internal signal generator (triangular/ square-wave) with BNC/4-mm output sockets for experiments involving modulation. **Note:** LEDs are subject to change in production. Thus the wavelengths of the LEDs within the Fiber optic transmitter can deviate from solutions given in the text.

736 412 Fiber optic receiver

Discretely assembled transimpedance amplifier with switchable conversion resistors. Separate DC and AC output. The DC output permits investigation of the dark current. With the AC output the advantages of modulation can be demonstrated. Built-in piezo loudspeaker.

736 421 Set of optical fibers and accessories

Set of PMMA fiber-optic cables with step index profile and 980/1000 µm core/cladding diameter. Plastic cladding with 2.2 mm external diameter.

1 Optical fiber, length 50 m
1 Optical fiber, length 20 m
1 Optical fiber, length 10 m
1 Optical fiber, length 5 m
1 Plastic optical fiber, transparent, length 10 m
  diameter 1 mm with connection piece 2.2 mm
1 Plexiglas directional coupler
1 Polishing tool
1 Abrasive cloth

736 429 Fiber optic microscope

The light is switched on, when the microscope is opened. In order to spare the batteries close the microscope after use.

Loose fiber adapter for checking the fiber end surfaces of bare PMMA sections. Only tighten when necessary.

LED characteristics

Theory

The diode characteristic in flow direction *(U_F* > 0) is described by the differential resistance r_F.

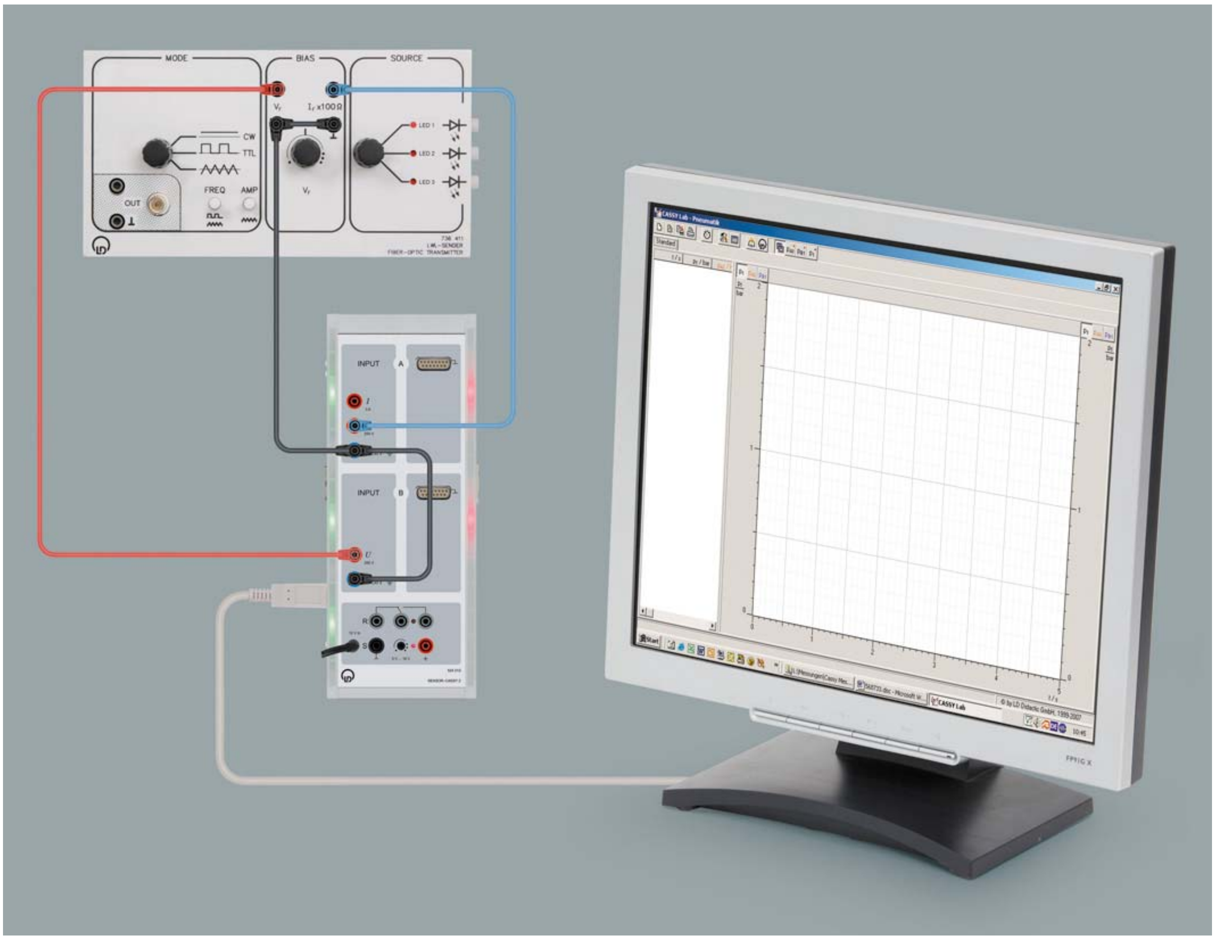
$$r_F = \frac{\Delta U_F}{\Delta I_F} \Delta$$

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 techniques with their attendant demands on linearity.

Material

1	736 411	Fiber optic transmitter
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	500 604	Safety connection lead 10 cm, black
2	500 644	Safety connection lead 100 cm, black
1	500 642	Safety connection lead 100 cm, blue
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	CW		R_C	---
BIAS	V_F → left	---	Output	---
SOURCE	LED 1 / 2 / 3			

Current-voltage characteristic

- Set up the shown experiment.
- Load the CASSY Lab example LEDCharacteristic.labx.
- Start the measurement by pressing *F9*.
- Record the current-voltage characteristic of the emitting LED in the forward direction, by slowly turning the potentiometer V_F to the right. Note: At the socket I_Fx100 Ω a voltage across an internal 100 Ohm resistor is measured. The diode current is thus converted into a voltage, which is easier to measure.
- Reaching the top right position of the potentiometer press *F9* again.
- Draw a tangent which intersects with the current-voltage characteristic. To do this make a right mouse click into the diagram *Fit Function / Best-fit Straight Line*. Mark the measurement values in the steep part of the characteristic by pressing the left mouse button. The parameter *A* is the inverse value of the differential resistance r_F:

$$r_F = \frac{1}{A}$$

Discuss the characteristic Determine the differential resistance r_F. What can be concluded about the differential resistance of the LED?

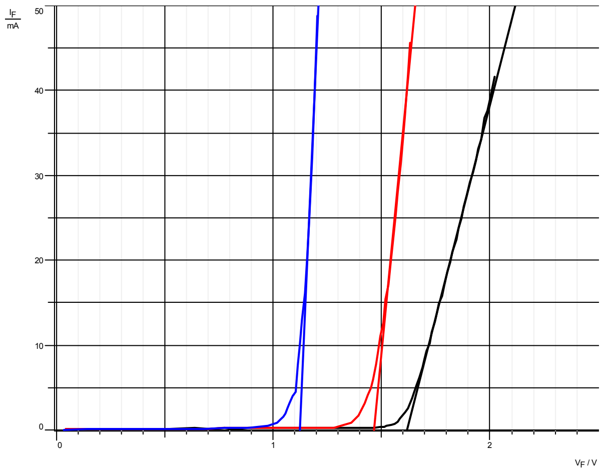
SOURCE	A/mAV^{-1}	r_F/Ω	V_S/V
LED 1			
LED 2			
LED 3			

- Repeat the recording and the evaluation of the characteristic for the LED 2 and LED 3.

Current-Power characteristic

- Load the CASSY Lab example LEDInputPower.labx.
- Start the measurement by pressing *F9*.
- Record the current-power characteristic of the emitting LED in forward direction by slowly turning the potentiometer VF to the right.
- Reaching the top right position press *F9* again.
- Display the current-power-characteristics in a common diagram.

Results

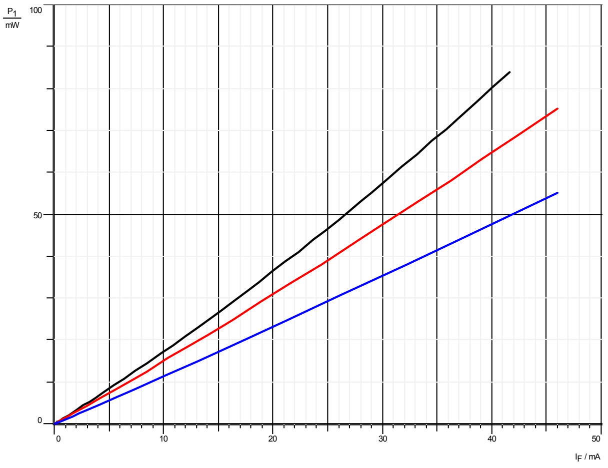


LED characteristics

blue: V_s = 1.2 V

red: V_s = 1.5 V

black: V_s = 1.7 V



Electrical input power of the LED

Summary

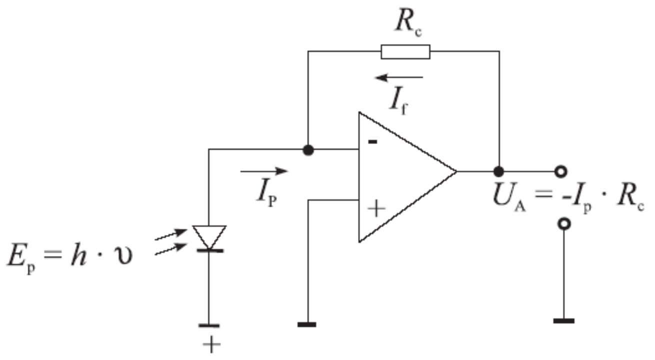
The LED practically blocks until the threshold voltage V_S are reached. Only after a further rise in the diode forward voltage U_F does the current increase steeply. If a tangent is applied to the steep part of the characteristic, than we obtain the threshold voltage at the point where the tangent intersects the voltage axis. The values obtained with CASSY Lab can be taken from the adjoining table.

SOURCE	A/mAV^{-}	r_F/Ω	V_S/V
LED 1	104	9.6	1.7
LED 2	266	3.8	1.5
LED 3	572	1.7	1.2

Note: Changes in electrical characteristics can arise due to modifications in the production of the LEDs.

The transimpedance amplifier

Theory



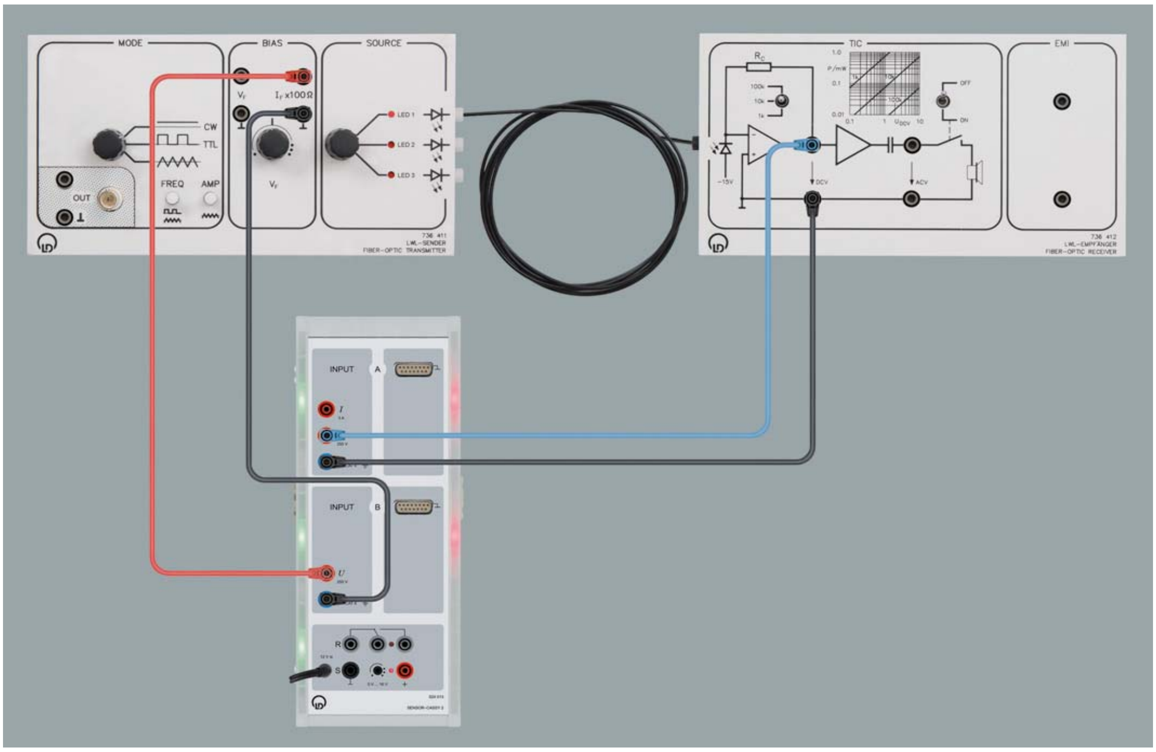
Transimpedance amplifier

In the fiber optic receiver 736 412 a PIN photodiode is used as the receiving element. The photodiode can be represented in the equivalent circuit diagram as a light-controlled current source. For this, it is biased in the blocking direction. Its reverse current I_P is then proportional to the intensity of the incident light. Using the shown circuit, the highly resistive current source of the photodiode is converted into a low resistance voltage source. If an ideal operational amplifier is assumed, the entire photocurrent I_P flows off across the conversion resistor designated R_C. Since the positive input of the op-amp is connected with respect to earth potential the output voltage is set to a value which is given by $-I_P*R_C$. Because the conversion factor between the input variable (photo current I_P) and output variable V_A has the dimension of an impedance, the circuit is called a transimpedance circuit. Due to the linearity existing between the incident light power and the output voltage, the transimpedance circuit can be employed for relative power measurements.

Material

1	736 411	Fiber optic transmitter
1	736 412	Fiber optic receiver
1	736 421	Set of fiber-optic waveguides and accessories
2	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
2	500 644	Safety connection lead 100 cm, black
1	500 642	Safety connection lead 100 cm, blue
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	CW		R_C	100 k
BIAS	V_F → left	10 m	Output	DCV
SOURCE	LED 1 / 2 / 3			

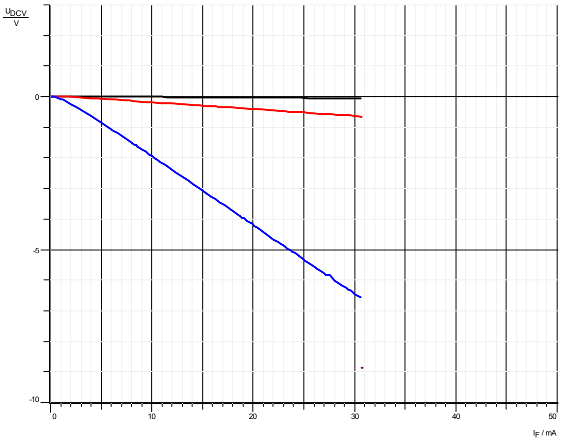
- Set up the shown experiment.
- Put the fiber at both endings firmly into the connectors.
- Load the CASSY Lab exampleTransimp.labx.
- Start the measurement by pressing *F9.*
- Slowly enhance the LED bias voltage (V_F) at the fiber optic transmitter.
- Reaching the top right position press *F9* again.
- Switch R_C to 10 K and 1 K. What do you observe?
- Remove the fiber from the receiver. Cover the photodiode with your finger. Enhance the sensitivity of the multimeters to 100 mV. Vary R_C. What do you observe?
- Connect the fiber with LED 2 at the fiber optic transmitter and switch SOURCE to LED 2.
- Start a new measurement by pressing *F4* and *F9.*
- Successively take the characteristic for LED 2 and R_C =1/10/100 k.
- Finally press *F9* again.
- Connect the fiber with LED 3 at the fiber optic transmitter and switch SOURCE to LED 3.

Results

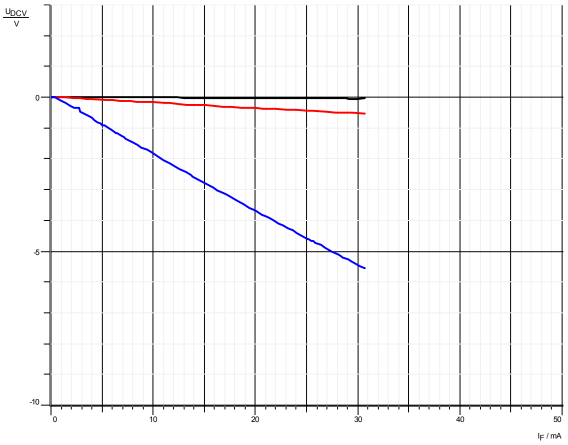
LED 1: (e.g. λ = 665 nm)

Interpretation:

The curve for R_C = 100 k has the steepest (negative) slope. There is a linear relationship between the output voltage of the transim-pedance amplifier and the forward current I_F of the LED.



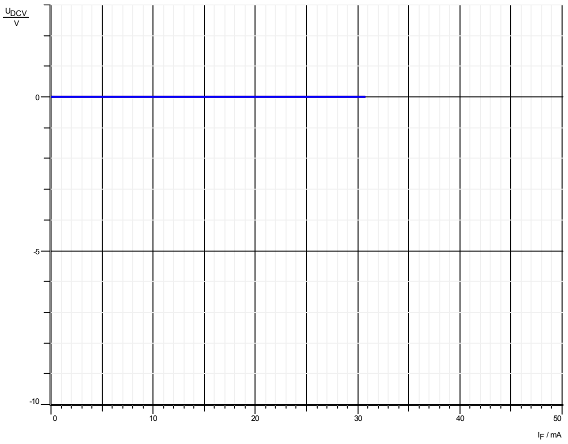
LED 2: (e.g. λ = 470 nm)



LED 3: (e.g. λ = 950 nm)

Interpretation:

No output voltage can be measured at the transimpedance amplifier. The attenuation of the optical fiber is too high for this wavelength.



Note: The wavelength of the light emitted by the transmitter LEDs may change due to the current availability of electronic components. The results of the experiments are not significantly affected.

Summary

Apart from the DC output due to dark current, there is a parasitic DC-voltage from the offset of the op-amp. The offset voltage is not influenced by R_C. The dark current and thus its parasitic voltage are very small. To reduce the influence of offset and dark current it is common use to modulate the light signal. The transimpedance amplifier needs an AC coupling for this.

Optical power of the emitting diodes

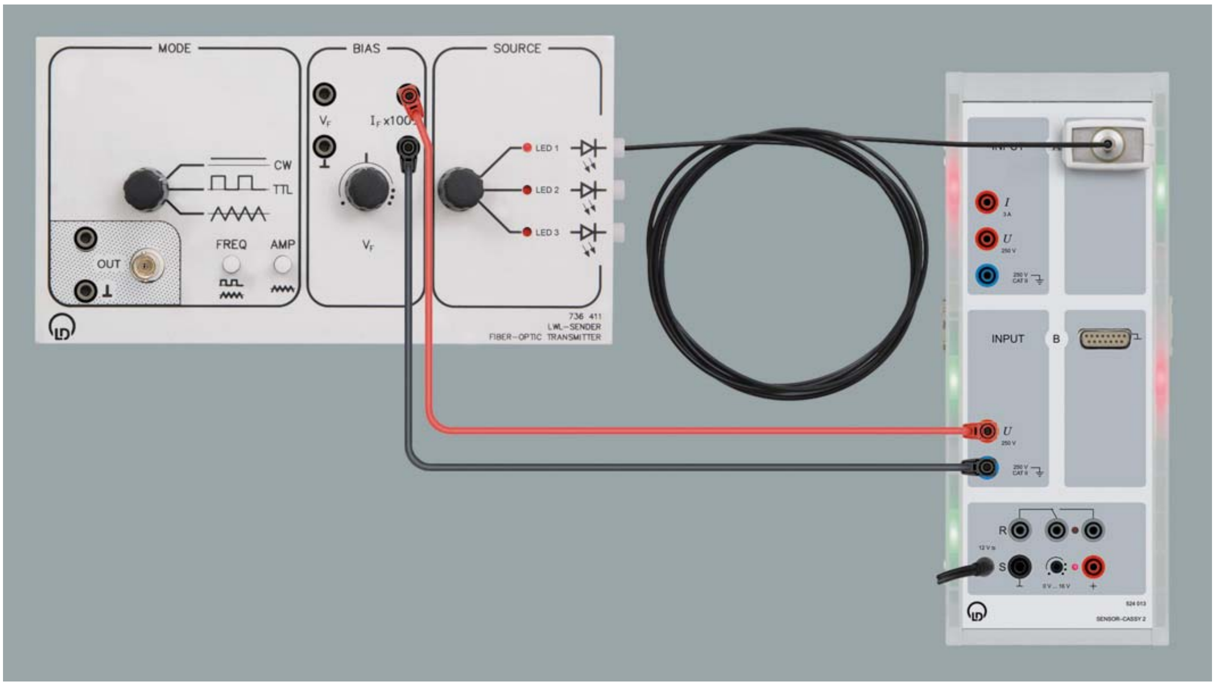
Theory

In this experiment the optical power P_2 emitted by the LED is determined. Since we already know from the last experiment the electrical power consumption P_1 of the LED as a function of the forward current the electro-optical efficiency η can be calculated as the quotient P_2/P_1 and represented as a function of the forward bias current I_F. An optical power meter is needed to measure the absolute optical power P_2. This is normally calibrated in dBm and gives a direct optical power reading.

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12 VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW			
BIAS	V_F → left	5 m	CASSY	channel A
SOURCE	LED 1			

Recording the power characteristic

- Set up the shown experiment.
- Put the fiber at both ends firmly into the connectors.
- Load the CASSY Lab example OpticPower.labx.
- Start the measurement by pressing *F9.*
- Turn the potentiometer V_F slowly to the right.
- Reaching the top right position, press *F9* again.
- Repeat the measurements for LED 2 and LED 3.

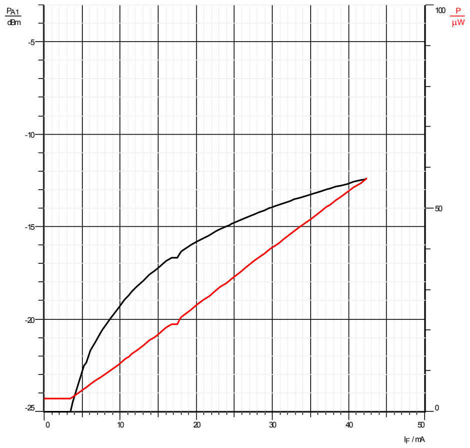
Determining the electro-optical efficiency

- Determine for each LED the forward voltage U_F, which comes with the forward bias currents I_F = 10/20/30 mA.
- Determine the electrical input power $P_1 = I_F \cdot U_F$.
- Calculate the electro-optical efficiency of the total transmission line $\eta = P_2/P_1$.
- Take the values for P_1 and P_2 from the CASSY tables.
- Note all values into the table.

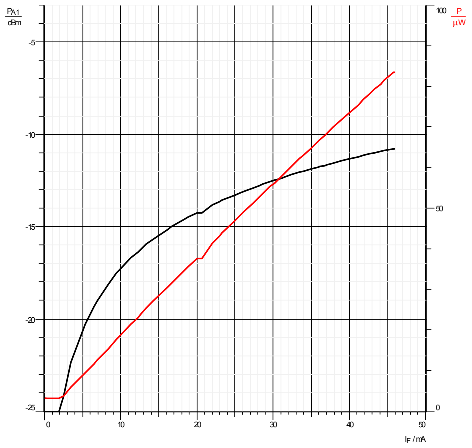
Electro-optical efficiency

	I_F = 10 mA			I_F = 20 mA			I_F = 30 mA		
SOURCE	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**
LED 1									
LED 2									
LED 3									

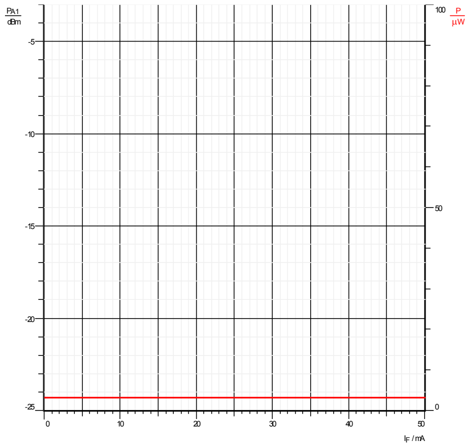
Results



Optical power of LED 1



Optical power of LED 2



Optical power of LED 3

Interpretation

- Only the PMMA-fiber with 10 cm gives a power measurement for the LED 3.
- The attenuation of the optical fiber is too large.

Electro-optical efficiency

	I_F = 10 mA			I_F = 20 mA			I_F = 30 mA		
SOURCE	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**
LED 1	16.8	11.4	0.07	36.1	26.2	0.07	58.1	40.3	0.07
LED 2	15.5	18.4	0.12	30.0	37.6	0.13	47.4	56.2	0.12
LED 3	11.3	3.1	0.03	24.8	3.1	0.01	38.0	3.1	0.01

Summary

The electro-optical efficiency η represents the ratio of optical output power P_2 to the supplied electrical power P_1. It is a measure of the power dissipation along the entire transmission link

- Crystal → LED housing
- LED housing → air
- Air → fiber optic waveguide

The total efficiency lies in the maximum range of around 1 %. The coupling losses of the plugs also reduce the efficiency of the entire link. The electro-optical efficiency of an LED lies at approximately η = 3...4%. It is that low because the beam generated remains in the LED due to absorption and reflection. The curve of the PI- characteristic is nearly linear, i.e. a continuous change in current results in a proportional change in optical power. If the current changes sinusoidal or square-wave shaped through modulation the consequence is a corresponding change in optical power. Therefore the LED is used particularly for signal transmissions in which it is essential to keep the shape of the transmitted signal. If one were to continue increasing the current I_F then we would eventually see saturation in the optical power characteristic. The reason for this is the power dissipation in the LED caused by higher currents. A portion of the electrical power supplied is converted into heat and not into light, power losses climb, the efficiency falls. In order to keep such a thermal excess to a minimum, efforts have to be made to ensure good cooling.

Notes

Deviations from the numerical values are possible because:

- Different power of the LED
- Different sensibility of the photodiode
- Conditions of the fiber ends (crashed, polished)

Absolute values are only meant as a guideline.

Light guidance by optical waveguides

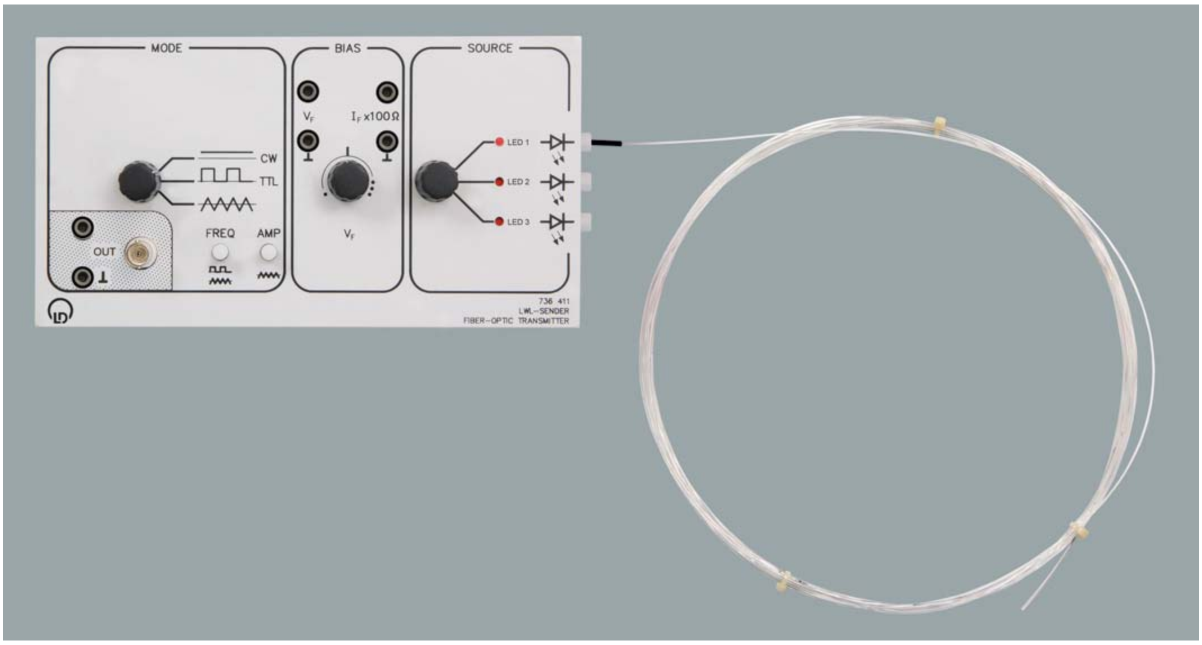
Theory

Large-core-fibers are optical waveguides with a large cross-section Φ in comparison to the wavelength λ. The PMMA fibers used in this training system with a core/clad diameter of 970/1000 µm are among these large-core fiber waveguides. In these kinds of fibers the guiding of light can be explained in terms of beam optics using the principle of total reflection. Only core-modes are guided over long disturbances. These are excited by light, which incidents on the front surfaces of the optical fiber below a particular maximum angle (acceptance angle).

Material

1	736 411	Fiber optic transmitter
1	524 0512	Optical power sensor S
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12 VAC
1	524 013S	Sensor-CASSY 2 Starter
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Guidance of optical fibers: Fiber optic transmitter with fiber, free end in front of white screen (sheet of paper)

Guidance properties of optical fibers

Presetting

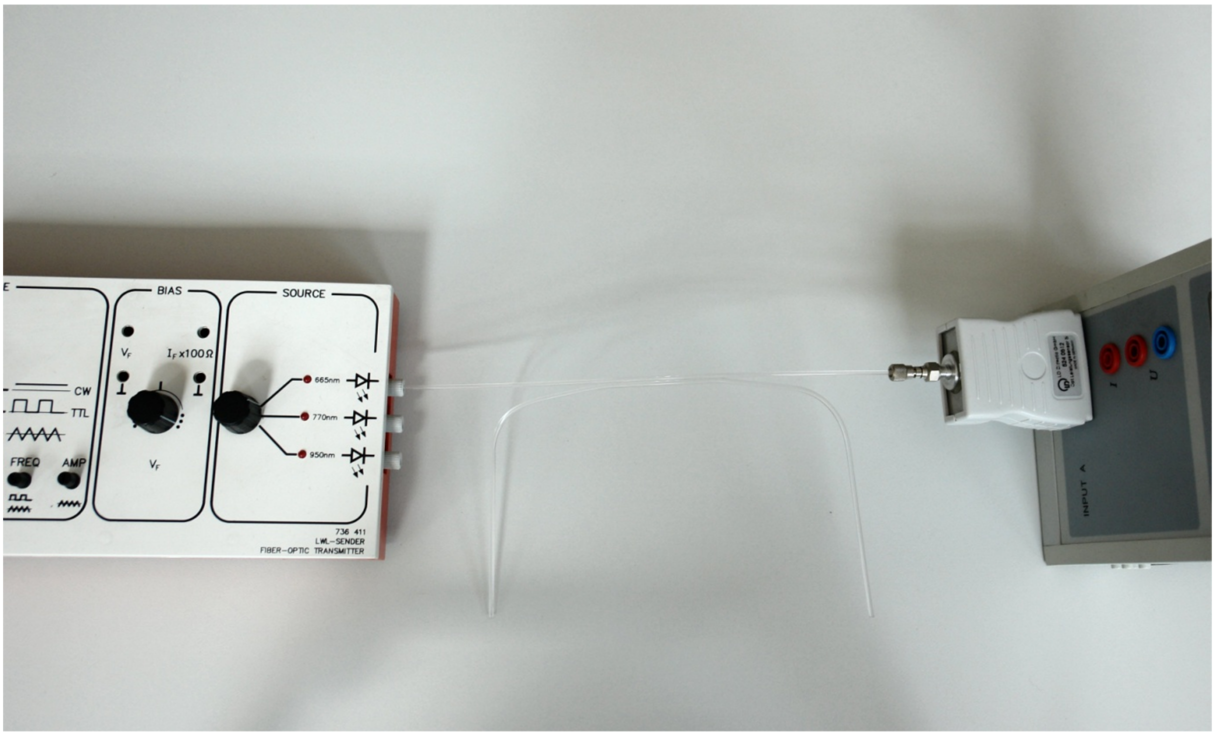
Fiber optic transmitter		Fiber		
MODE	CW			---
BIAS	V_F → right	20 m		---
SOURCE	LED 1	transparent		

Note

The experiment results are best when performed in slightly dimmed conditions.

- Put the transparent fiber into the receptacle of the LED 1.
- Hold the emitting end of the fiber flat on a white piece of paper. Observe how the light exits. What happens when you slightly bend the roll of fiber?
- Make several sharp kinks about 2 cm from the end of the fiber. What do you observe? Scratch the surface open at a few places of the bent piece of fiber. What do you observe?

Total reflection



Total reflection: Fiber optic transmitter, acrylic glass coupler and optical power sensor

The acrylic glass coupler is used here only as the transfer medium between the fiber optic transmitter and the optical power sensor. The Sensor-CASSY is placed *upside down* for easy connection of the coupler.

Presetting

Fiber optic transmitter		**Fiber**	**Optical power sensor S**	
MODE	TTL			
BIAS	$V_F \rightarrow$ right	acrylic glass coupler		---
SOURCE	LED 1		CASSY	channel A

- Set up the experiment with Sensor-CASSY and optical power sensor S as shown.
- Load the CASSY Lab example TotalReflexionOPS.labx.
- Measure the optical power (Measurement „undisturbed“).
- Now touch the acrylic coupler with your finger. Measure the optical power (Measurement „disturbed“).
- Repeat the experiment with the transparent optical fiber. For this insert the free end into the optical power sensor and hold it there tight. Try to keep from shaking! Enter your measurements into the table.

Optical power / dBm

Measurement undisturbed	Measurement disturbed

Variants

- Try other LED.

Results

Guidance properties of optical fibers

When the light leaves the transparent fiber, this occurs with a more or less clearly recognizable beam cone. Slight pressure on the fiber leads to an increase of bend attenuation. The rolled up fiber illuminates weakly in the area where small turn radii prevail. Sharp kinks cause severe leakage out of the optical fiber. Then the fiber optic waveguide looses to a great degree its capacity to guide light waves. The fiber cladding is destroyed by excessive scratching or roughing of the surface. The total reflection now occurs at the external surface bordering on the air and can easily be distorted. This also becomes visible by a weak illumination of the fiber.

Total reflection

Optical power / dBm

Measurement undisturbed	Measurement disturbed
-11.9 dBm	-15 dBm

Acrylic glass does not have any core jacket structure. It guides light waves through total reflection at the glass-air boundary. According to the Goos-Hänchen theory, during total reflection the light waves penetrate several wavelengths deep into the medium with the lower refractive index and then run along the border as surface waves before they return into the medium with the higher refractive index again. These surface waves can easily be disturbed by touching, which leads to a drop in optical power being transmitted along the acrylic glass link. In contrast to simple acrylic glass, the transparent optic fiber has a core jacket structure. The total reflection necessary for light transport occurs here at a boundary protected from external contact. Consequently the optical fiber cannot be disturbed.

Attenuation

Theory

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 the measurement is performed according to the cutback method. Here the optical power P_2 is measured at one end of a known cable length l. 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 measurement method is 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 experiments. Thus for the purpose of experimentation the attenuation measurements are described as throughput measurements on premade optical fibers of different length. A typical parameter for an optical waveguide is the attenuation coefficient *a,* which is defined as attenuation per km of waveguide material. The attenuation of an optic waveguide for a fixed wavelength is given by:

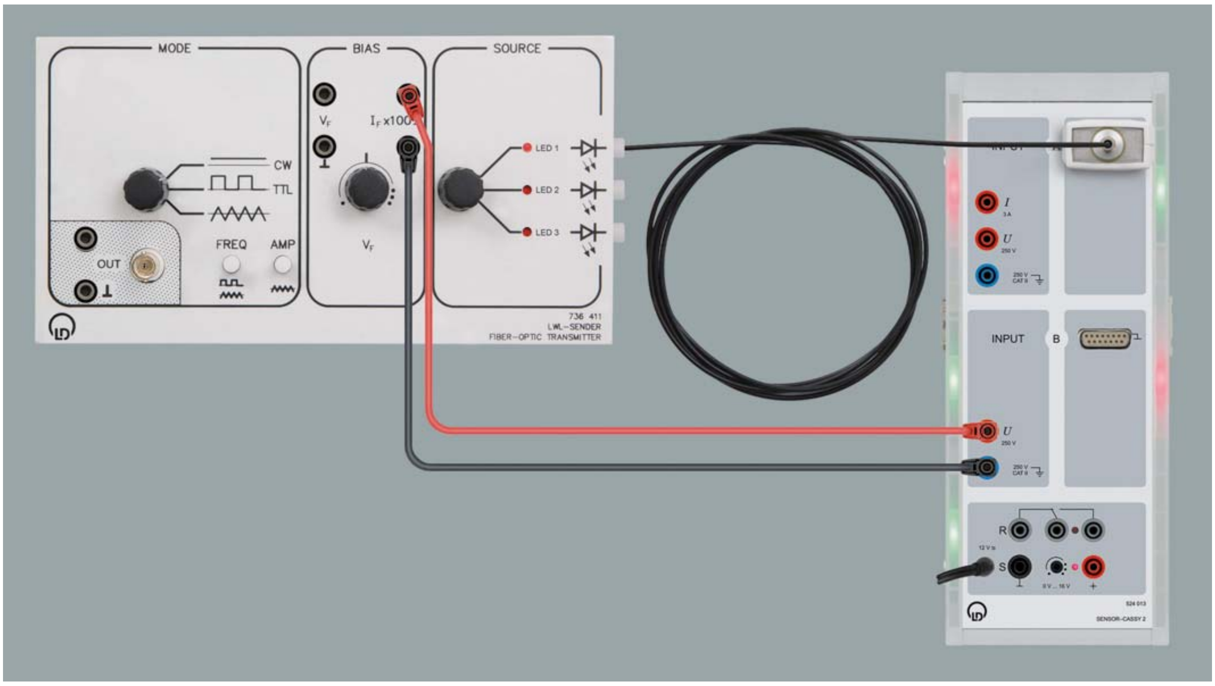
$$\frac{a}{dBkm^{-1}} = \frac{10.000}{\Delta l}\log\frac{P_1}{P_2}$$

Enter Δl in m.

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

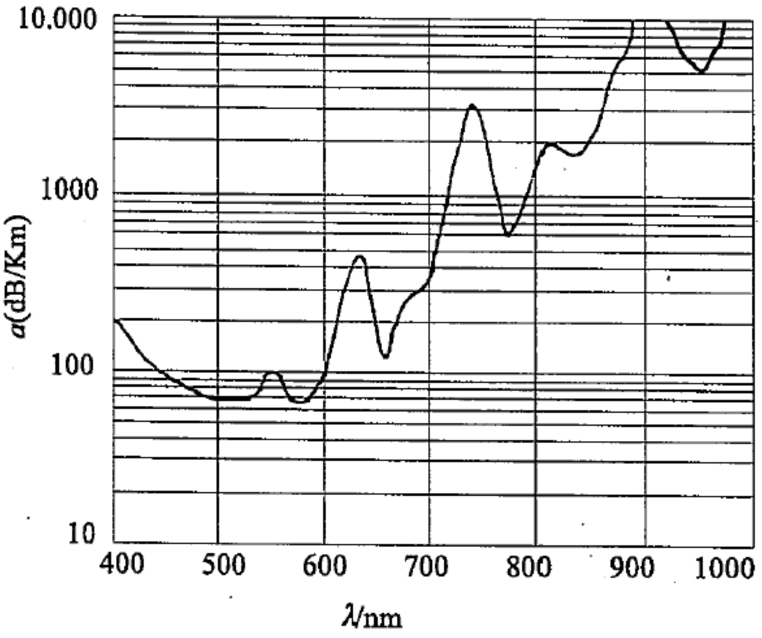
Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	all		
BIAS	V_F → right	lengths	CASSY	Input A
SOURCE	LED 1/2/3			

- Set up the shown experiment
- Select LED 1 with SOURCE.
- Put the fiber with *l* = 5 m firmly into the connector of the LED.
- Load the CASSY Lab example Attenuation.labx.
- Right mouse click into the instrument PA1 activate *settings sensor input* → 0 ←. The display changes to 0 dB.
- Measure successively the fibers with *l* = 10/20/50 m.
- Calculate the attenuation a/dBkm^{-1}. For that, insert the attenuation values into the appropriate formulas.
- Repeat the measurement for LED 2 and LED 3 respectively. If necessary, change the settings in CASSY Lab.

I_F/mA	SOURCE	PA1/dB				a/dBkm^{-1}
		l = 5 m	l = 10 m	l = 20 m	l = 50 m	
42.45	LED 1					$a = \frac{1000}{45} a_{50} =$
	LED 2					$a = \frac{1000}{15} a_{20} =$
	LED 3					$a = \frac{1000}{5} a_{10} =$

Variant

- Demonstrate the bend attenuation.



Principal characteristic of attenuation for PMMA

Results

I_F/mA	SOURCE	PA1/dB l = 5 m	l = 10 m	l = 20 m	l = 50 m	a/dBkm^{-1}
42.45	LED 1	0.0	-0.4	-3.0	-9.3	$a = \frac{1000}{45} a_{50}$ = 207
	LED 2	0.0	-3.7	-9.9	<-15.0	$a = \frac{1000}{15} a_{20}$ = 660
	LED 3	0.0	-14.9	<-19.7	---	$a = \frac{1000}{5} a_{10}$ = 3000

Summary

Mean fiber attenuation for die LED 3 is hard to estimate: *a* > 3000 dBkm^{-1}

Interpretation

Of the two attenuation minima between 500 nm and 700 nm the one at λ = 650 nm is most suitable for link lengths up to 100 m. Furthermore, the switching times for the red LED are shorter than for the possible green emitter at λ = 560 nm. Consequently LEDs in the visible red range (λ = 665 nm) are particularly suitable for data transmissions using PMMA. For short link lengths in the range of several meters favorable power /cost ratios can be achieved using very powerful IR-emitters, in spite of the enormous fiber attenuations. If the fiber is bent too severely, then modes are guided flatly through the cladding and out of the waveguide. In this case leaky modes are exited. The propagation in the fiber optic core is also hindered by scattering and absorption. The former can occur at faulty sites (e.g. imperfections or trapped crystals) or at areas with fluctuating dielectric constants. The latter is called Rayleigh scattering. Another important cause for power losses results when light causes molecules to oscillate and is thus converted into thermal energy. Consequently, only those wavelength ranges are used for signal transmission, in which minima arise in the attenuation characteristic curve. Such ranges are called optical windows.

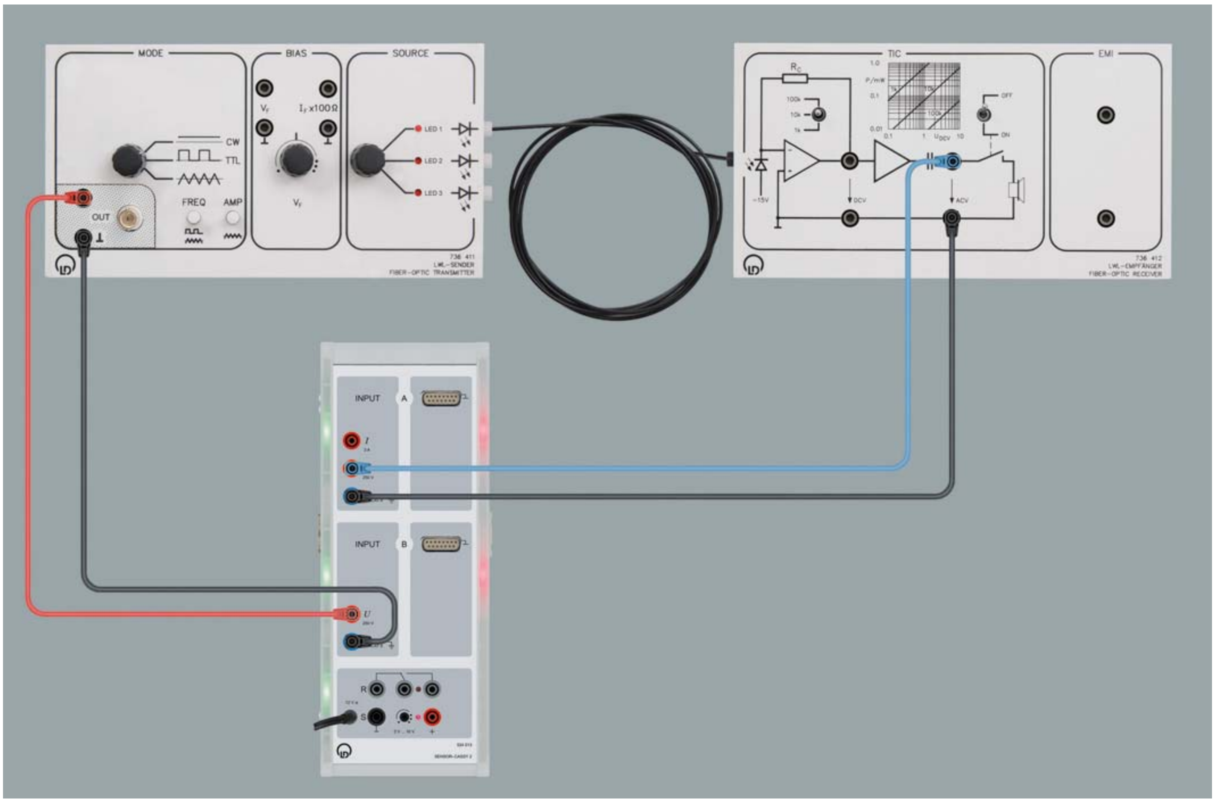
Signal transmission with optical fibers

Material

1	736 411	Fiber optic transmitter
1	736 412	Fiber optic receiver
1	736 421	Set of fiber-optic waveguides and accessories
2	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
2	500 644	Safety connection lead 100 cm, black
1	500 642	Safety connection lead 100 cm, blue
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Analog modulation

Carrying out the experiment



Fiber optic transmitter: Use the OUT-sockets

Fiber optic receiver: Use the AC V-output

Presetting analog modulation

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	Triangle		R_C	10 k
FREQ	→ min	10 m	Output	ACV
AMP	→ max		loudspeaker	ON
BIAS	$V_F \rightarrow$ variable			
SOURCE	LED 1			

- Set up the shown experiment
- Load the CASSY Lab example Analog.labx.
- Start the measurement by pressing *F9.*
- Enhance the bias voltage of the LED. For it turn the potentiometer V_F slowly to the right.
- Observe the modulating signal V_{OUT} and the received signal V_{ACV} for different bias voltages: BIAS: min. / middle / max.
- Select a frequency for maximum sensitivity of the loudspeaker.
- Sketch the oscillogram with the modulating signal of the signal generator and the demodulated signal at the output of the receiver V_{ACV}.
- Discuss the situation for analog modulation.

Setting the operation point for analog modulation

- Display the current I_F and the voltage V_F at the LED (fiber optic transmitter) for optimum operation point. An optical transmission system consists of which components?

Fiber optic transmitter	
MODE	triangle
FREQ	→ min
AMP	30%, mean, 60° max
BIAS	$V_F \rightarrow$ variable
SOURCE	LED 1

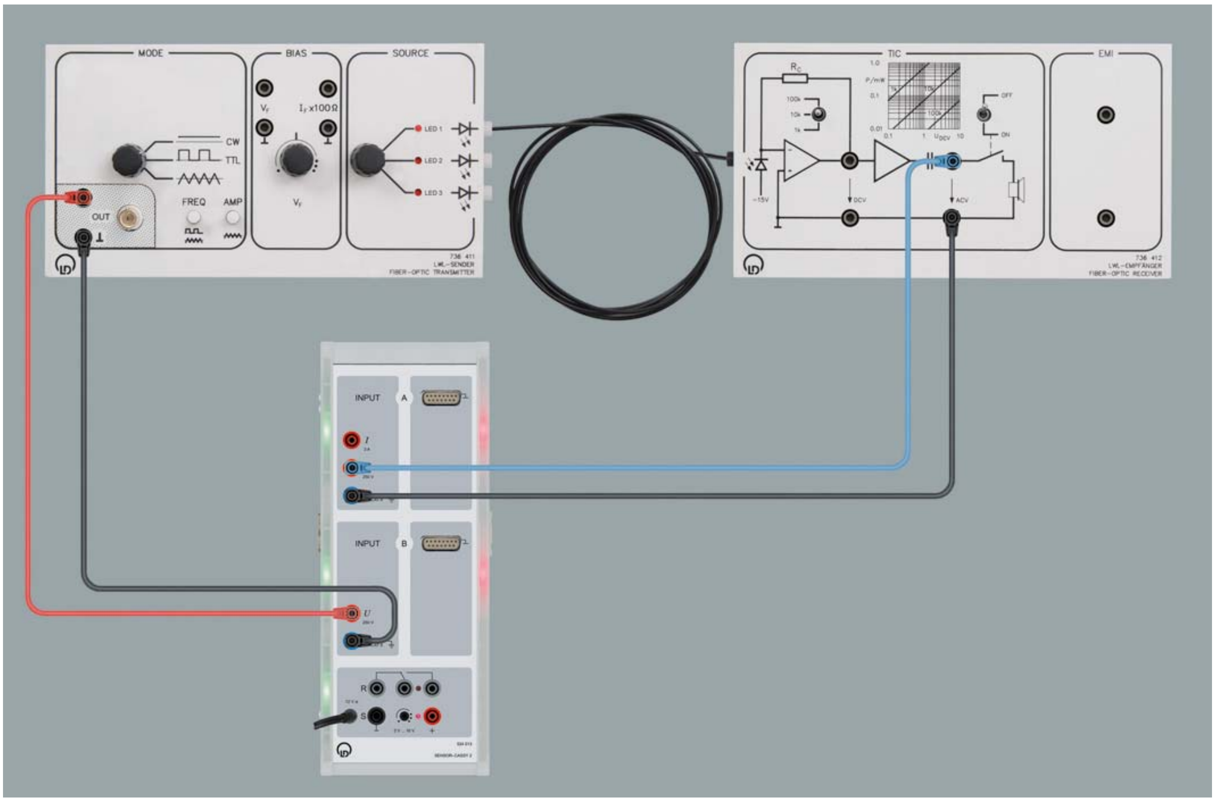
Note: The reduction of the amplitude: AMP < 30% gives parasitic effects.

- Load the CASSY Lab example AnalogCurrent.labx.
- Start the measurement by pressing *F9.*
- Enhance the bias voltage of the LED. For this turn the potentiometer V_F slowly to the right.

Variants

- Change the frequency of the modulating signal.
- Use another LED.
- Switch the loudspeaker on / off.
- Bend the fiber carefully and observe the attenuation.

Digital modulation



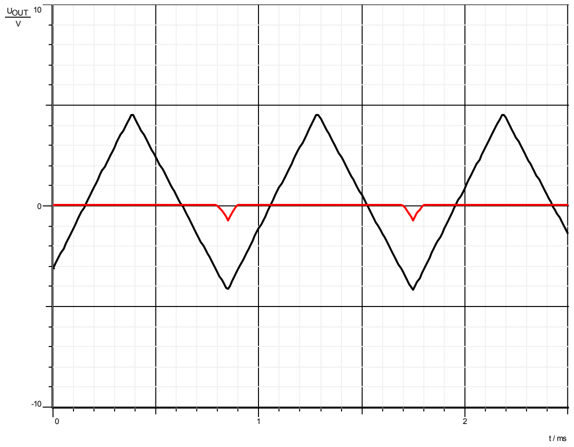
Presetting digital modulation

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	TTL		R_C	10 k
FREQ	min / max / random	10 m	Output	ACV
SOURCE	LED 1		loudspeaker	ON

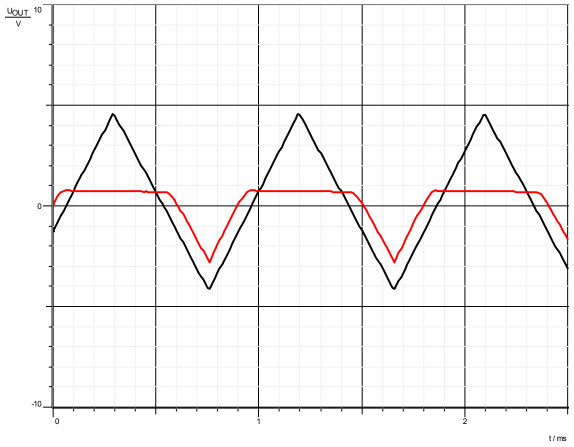
- Carrying out the experiment as for analog modulation.
- Load the CASSY Lab example DigitalCurrent.labx.
- Start the measurement by pressing *F9.*
- Sketch the oscillograms of the modulating signal (fiber optic transmitter: OUT) as well as the output voltage U_{ACV} at the fiber optic receiver. Briefly describe the oscillograms!
- Distinguish the signal parameters for analog and digital transmission.

Results

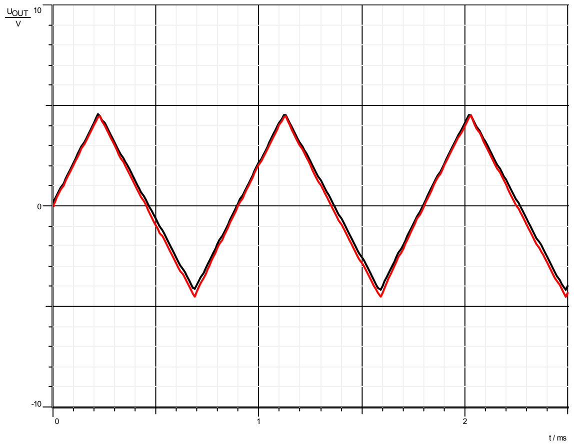
Analog modulation



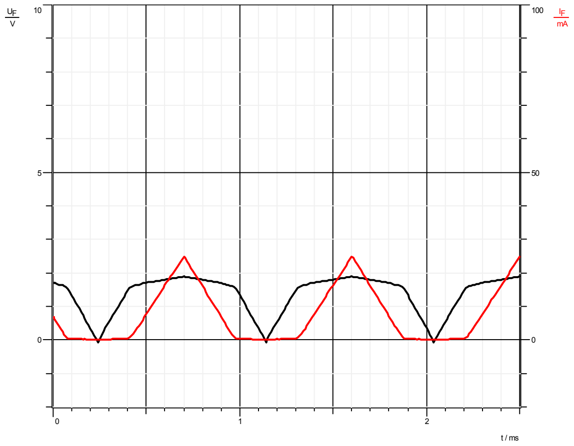
Bias minimum
Black: modulating signal at OUT
Red: demodulated signal at ACV



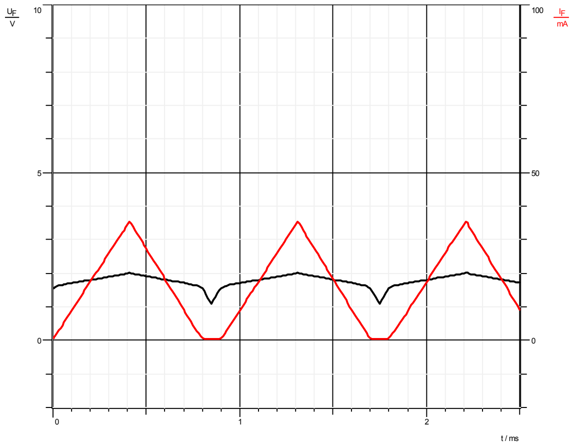
Bias middle
Black: modulating signal at OUT
Red: demodulated signal at ACV



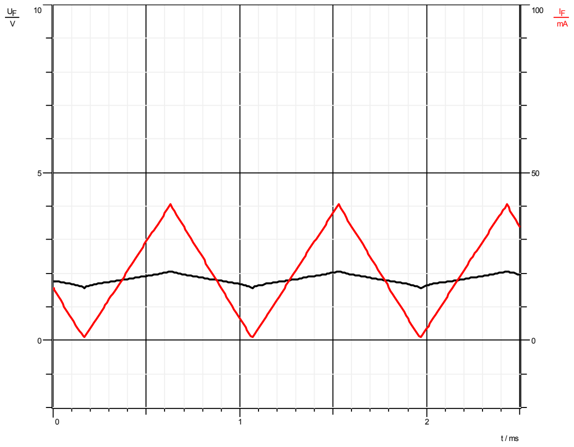
Bias maximum
Black: modulating signal at OUT
Red: demodulated signal at ACV



Fiber optic transmitter: current (red) and voltage (black) at the LED, AMP = 30% (ca.)

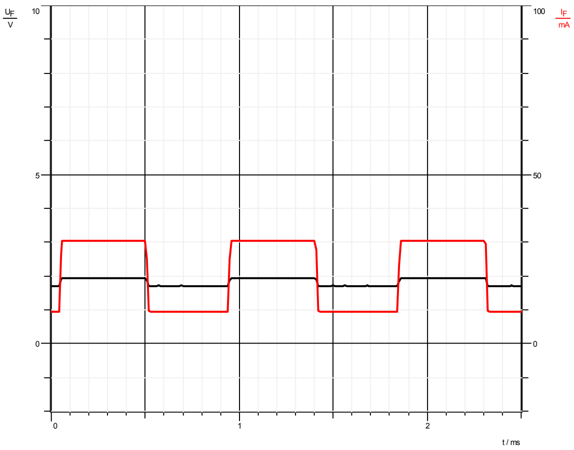


Fiber optic transmitter: current (red) and voltage (black) at the LED, AMP = mean (ca.)



Fiber optic transmitter: current (red) and voltage (black) at the LED, AMP = 60% (ca.)

Digital modulation



Black: modulating signal
Red: demodulated signal at ACV

Summary

Analog modulation

Analog fiber optic technology is primarily used in instrumentation, open- and closed-loop control technology, where particularly high demands are made regarding the linearity of the transmission channel. The linearity is mainly influenced by the current-power characteristic of the LED. Non-linear properties of the emitter diodes lead to signal distortion. The phase shift between input and output signal amounts to $\phi = 0°$. The wanted signal shows no recognizable non-linear distortion. Consequently, the Total harmonic distortion (THD) factor is small. An amplitude attenuation appears here as a form of linear distortion. This can be corrected using a suitable amplifier (here by selecting R_c). The distortions in the output signal at the fiber optic receiver are dependent on the distortions of the diode current of the LED.

An optical transmission link consists of five components:

- Modulator (control electronics of the LED)
- Electro optical transducer (LED)
- Optical fiber (PMMA)
- Opto-electrical transducer (PIN-photodiode)
- Demodulator (electronics, e.g. transimpedance amplifier)

The forward current I_F cannot be negative ($I_F > 0$). In the range of small diode currents the characteristic changes its differential resistance. For current modulation of the LED, this leads to distortions.

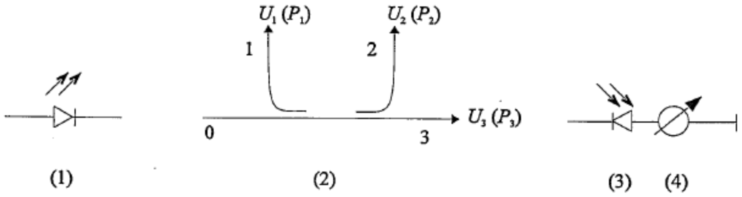
Digital modulation

The modulating digital signal does not require any operating point calibration. In digital transmission links receivers with threshold value decision are used. As long as the threshold value is exceeded by the signal coming from the photodiode, a disturbance free data transmission is possible. Analog signals are described by the frequency, amplitude as well as their curve shapes. In contrast, digital signals in TTL format are always rectangular. They have a fixed level and are defined by their bit frequency, i.e. their transmission capacity. When transmitting digital signals, it must be guaranteed that the transmitted signal can be reproduced in the receiver with sufficient accuracy. To do this, a minimum optical power (minimum number of photons) is required at the receiver, which ensures that a transmitted light pulse - one bit - is recognized.

Fiber coupler

Theory

In the previous experiments transmission links were considered to be point-to-point connections between two terminal devices. Using optical couplers it is possible to use a fiber jointly by several transmitters and receivers. For example in an optical LAN, multiplex signals from different terminals are transmitted via one optical fiber. On the transmitter side the signals from several sources are combined by a multi-port coupler and fed to an outgoing optical fiber. On the receiver side a wavelength selective coupler performs the distribution of the signals to the appropriate receiver. The coupler used in this training system consists of two uncoated dielectric lines, which have direct contact with each other along a length of approx. 45 mm. The lack of optical cladding in this coupler leads to considerable susceptibility to disturbance caused by total reflection. For that reason in real couplers the area outside the coupling zone has to be surrounded by an optical cladding. The power distribution in a coupler is expressed by the so-called coupling factor *CR*. The CR is a decisive quantity of couplers and thus it is investigated in the subsequent experiments.



Schematic representation: (1) light source (2) coupler (3) photo detector

For the coupling ratio $CR_{0\text{-}1}$ between port 0 and port 1 the following holds true:

$$CR_{0-1} = \frac{P_1}{P_1 + P_2 + P_3}$$

Usually the optical power emerging at port 3 is much bigger than P1 and P2. Thus:

$$CR_{0-1} \approx \frac{P_1}{P_3}$$

Or, in logarithmic notation:

$$\frac{CR_{0-1}}{dB} \approx \frac{P_1}{dB} - \frac{P_3}{dB}$$

If we calibrate P_3/dB =, we get the following relationship:

$$\frac{CR_{0-1}}{dB} \approx \frac{P_1}{dB}$$

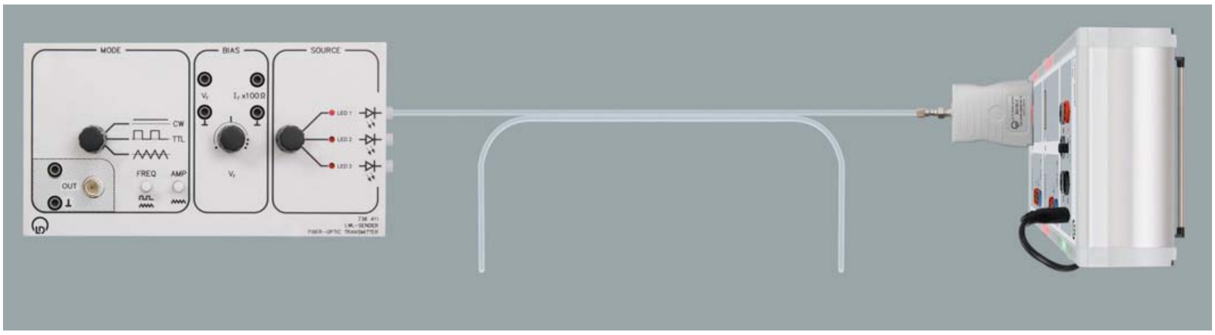
Respectively

$$\frac{CR_{0-2}}{dB} \approx \frac{P_2}{dB}$$

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Sensor-CASSY „upside down“

Presetting of the multiport coupler

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW			
BIAS	V_F → right	acrylic glass coupler	CASSY	channel A
SOURCE	LED 1 / 2 / 3			

Notes

- The optical coupler is made of acrylic glass. Handle with care and avoid strong bending.
- Before inserting the coupler, the screw nuts of the LED-diode have to be loosened.
- Make sure that the coupler is inserted deeply enough into the receptacles of the LED and the optical power sensor.
- Softly align the fiber optic transmitter, the coupler and the optical power sensor, until the maximum output signal is indicated.
- The ports 0 and 3 can be interchanged. This also inverts the function of the ports 1 and 2.
- It`s common practice to take the absolute value of the coupling ratio (no negative quantities).

Measuring the coupling ratio $CR_{0\text{-}2}$

- Set SOURCE to LED 1.
- Set up the above shown experiment.
- Load the CASSY Lab example CR02.labx.
- Make a right click into the instrument “Optical Power P_{A1}“ to activate *Settings*. Click on: → 0 ←. Reduce V_F, if the display is blinking.
- The display of $CR_{0\text{-}2}$ changes to 0.0 dB.
- Connect the optical power sensor to port 2 of the coupler.
- The display of the meter changes to the actual coupling ratio $CR_{0\text{-}2}$. List the value $CR_{0\text{-}2}$ in the table.
- Subsequently set the SOURCE to LED 2 and LED 3 respectively.
- Repeat the experiment.

Measuring the coupling ratio $CR_{0\text{-}1}$

- Set SOURCE to LED 1.
- Set up the above shown experiment.
- Load the CASSY Lab example CR01.labx.
- Make a right click into the instrument “Optical Power P_{A1}“ to activate *Settings*. Click on: → 0 ←. Reduce V_F, if the display is blinking.
- The display of $CR_{0\text{-}1}$ changes to 0.0 dB.
- Connect the optical power sensor to port 1 of the coupler.
- The display of the meter changes to the actual coupling ratio $CR_{0\text{-}1}$. List the value $CR_{0\text{-}1}$ in the table.
- Subsequently set the SOURCE to LED 2 and LED 3 respectively.
- Repeat the experiment.

SOURCE	$CR_{0\text{-}1}$/dB	$CR_{0\text{-}2}$/dB
LED 1		
LED 2		
LED 3		

Results

Principle of the multimode fiber coupler

SOURCE	CR_{0-1}/dB	CR_{0-2}/dB
LED 1	20.1	6.7
LED 2	18.5	8.9
LED 3	21.0	6.1

Interpretation

- Deviations due to material fluctuations of the coupler are possible. Common values are:

  CR_{0-1}: 18…22 dB

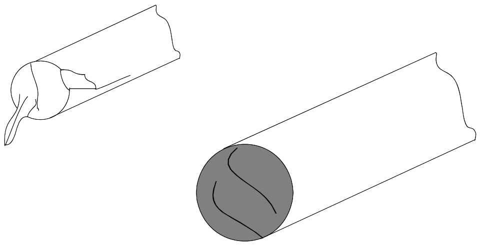
  CR_{0-2}: 6...9 dB

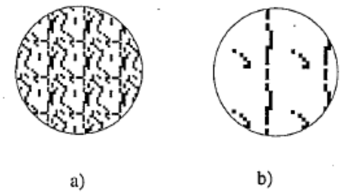
- The coupling ratio in forward direction CR_{0-2} is much bigger than the coupling ration CR_{0-1} in reverse direction. Thus the coupler can be used as directional coupler.

Preparation of fiber ends

Theory

If optical fibers have to be coupled to each other in a network via connectors, high demands are made on the integrity and cleanliness of the ends. Contaminated or even damaged fiber ends generally lead to increased coupling losses. In glass fibers damaged fiber ends frequently have fractures on the edges of the fibers or protruding whiskers. One often sees scratches or pits along the length of greater or lesser severity on PMMA optical fibers. The figure shows the corresponding faults.





Fiber ends: a) unpolished b) polished

In order to achieve smooth, flat and flush fiber ends running at right-angles along the axis, two methods are used in practice for glass fibers:

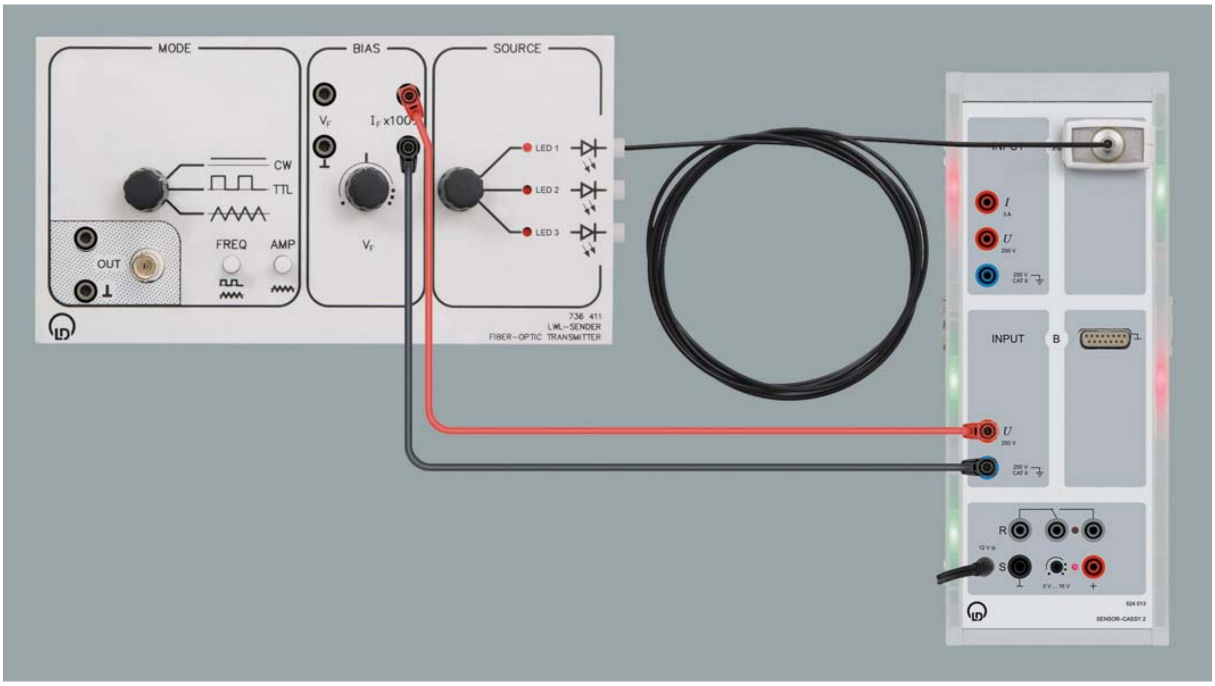
- notching and (defined) breaking off
- grinding and polishing

For the PMMA fibers only the grinding and polishing methods come into question.

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	736 429	Fiber-optic microscope
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

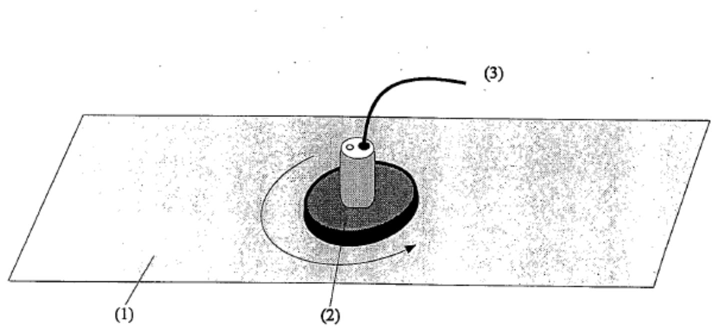
Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	all lengths	CASSY	channel A
BIAS	V_F → right			
SOURCE	LED 1			

- Set up the shown experiment. Use the fiber optic transmitter, the fiber and the optical power sensor S.
- Scratch the ends of the PMMA-fiber slightly with the abrasive paper.
- Control the result with the fiber-optic microscope.
- Load the CASSY Lab example Coupler.labx.
- Right click into the instrument P_{A1}. Activate *Settings sensor input* → 0 ←. The display changes to 0 dB.
- Start the measurement by pressing *F9*.
- Use the smooth rear side of the abrasive paper for polishing. Use a strip of scotch tape to fasten an approx. 150 mm long segment of the abrasive paper onto a smooth surface (e.g. bench top). Be careful: The surface of the bench should not be susceptible to scratches.



1: Abrasive paper
2: Polishing tool
3: Fiber

- Insert one fiber end into the appropriate hole of the polishing tool. Apply the tool to the abrasive paper and make circular polishing motions. After the polishing procedure, clean the fiber ends with a soft towel or something similar. Reinsert the optical fiber into the experiment and carry out the power measurement again. Enter the measurement results into the table. Determine the gain *g* obtained by polishing.

l/m	g/dB
5	
10	
20	
50	

Notes

- The fiber optic microscope (736 429) can be used to check the quality of the fiber ends. Use the loose fiber optic adapter for PMMA optical fibers (ϕ = 2,2 mm contained in the scope of delivery). The internal illumination of the microscope is switched on automatically by unfolding. Fold up again after each use of the microscope, otherwise you will use up the battery. In order to focus correctly, the optical fiber should be pushed in approximately to the interior edge of the adapter. Focusing is performed by turning the knurled wheel.

- The polishing tool has one drilled hole to accommodate the PMMA optical fiber with buffer (ϕ = 2.2 mm) and one drilled hole for PMMA optical fibers without buffer (ϕ = 1 mm). The latter hole can be used to polish the transparent optical fibers.

Results

Preparation of fiber ends

l/m	g/dB
5	1.3
10	0.9
20	1.1
50	0.7

Interpretation

The polishing of one fiber end (PMMA) results in a power gain of 25% (+1.0 dB) approximately.

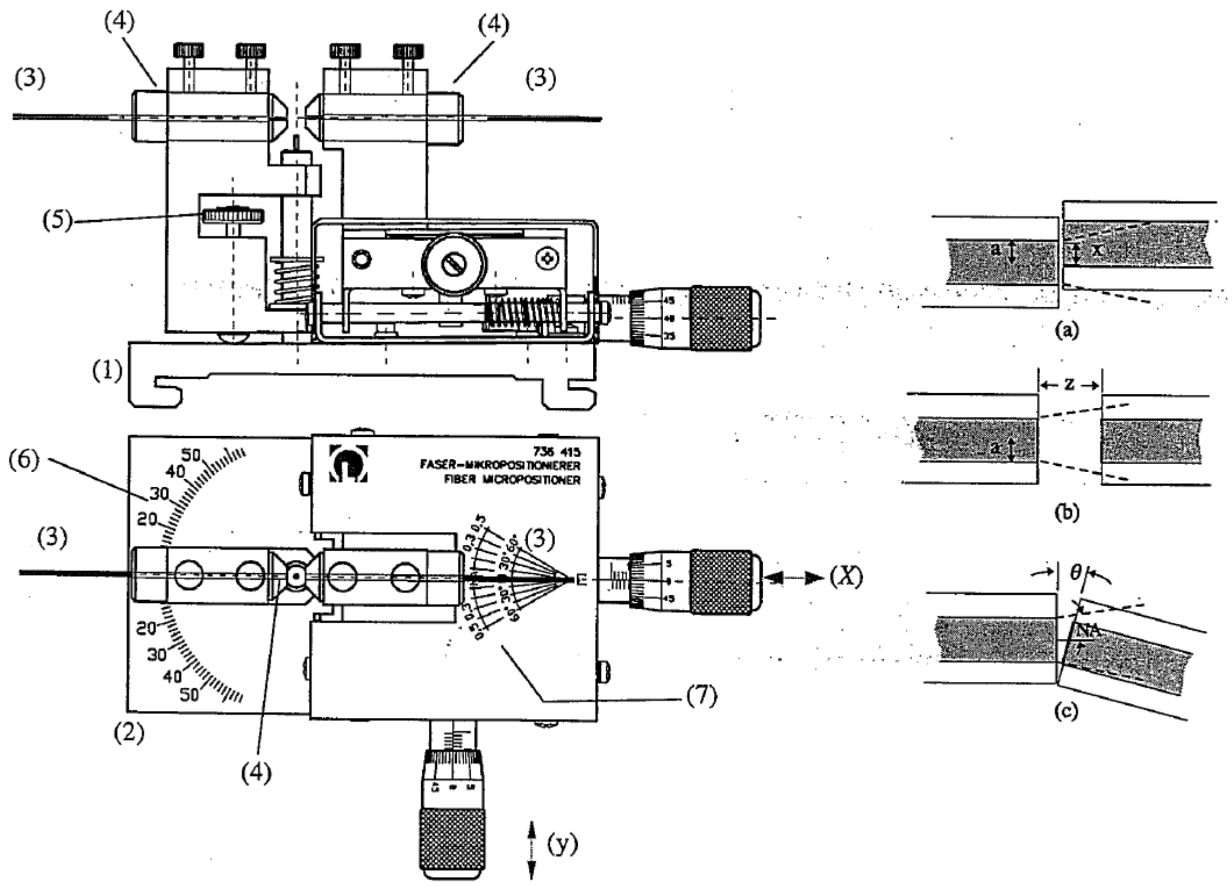
Coupling losses

Theory

Plug connections can contribute additional coupling losses in an optical transmission network due to the following fault sources:

- transversal offset
- longitudinal offset
- angular offset (axes of the optical fibers are at an angle to each other)

Optimally both fiber end faces should be lined up evenly and without any air gaps when two optical fibers are connected to each other.



a: transversal offset

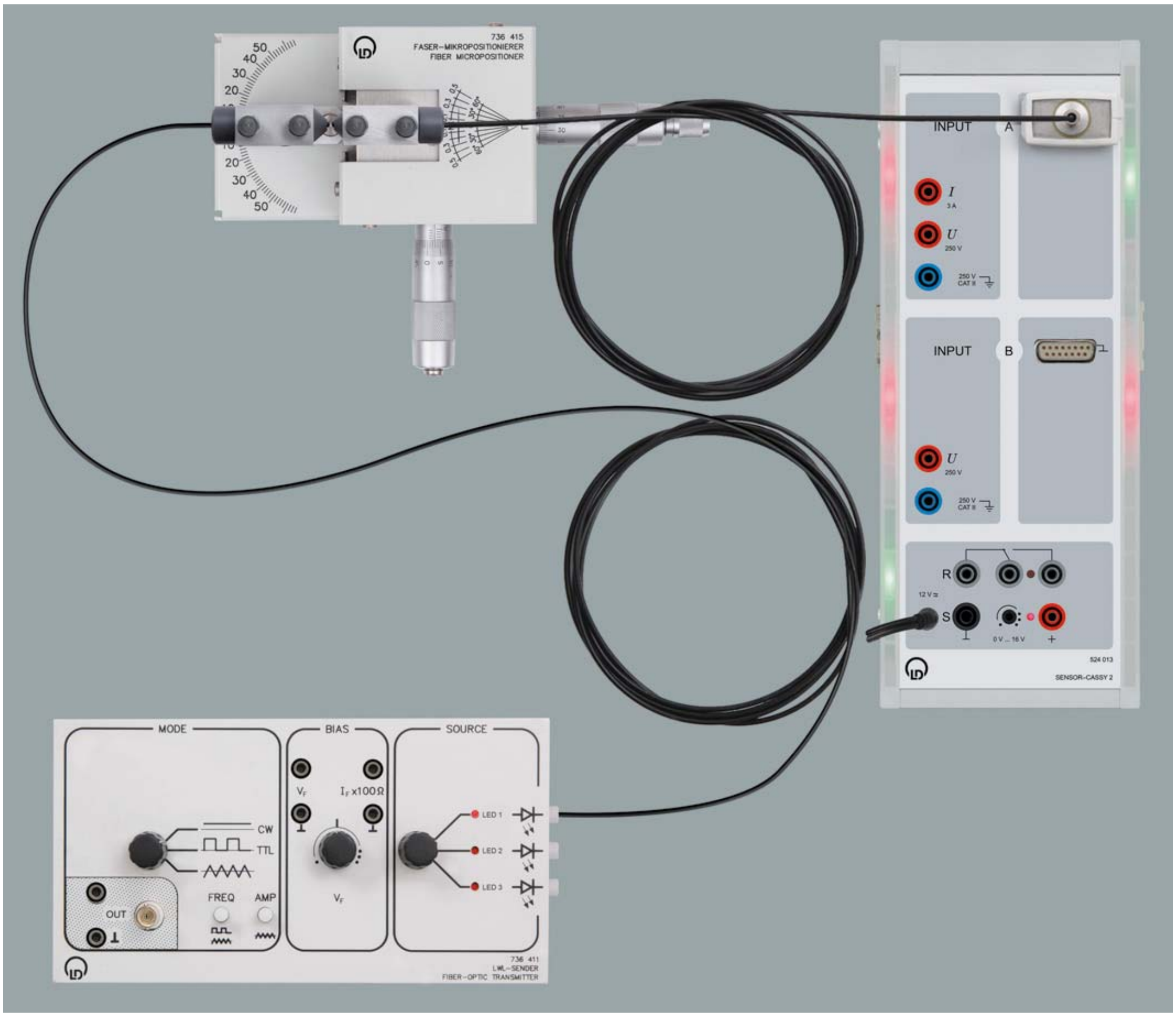
b: longitudinal offset

c: angular offset

Material

1	736 411	Fiber optic transmitter
1	736 415	Fiber micropositioner
1	736 421	Set of fiber-optic waveguides and accessories
1	736 429	Fiber-optic microscope
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	fibers		
BIAS	V_F → right	from	CASSY	channel A
SOURCE	LED 1	micropositioner		

Longitudinal offset

- Set the X-micrometer of the fiber-micropositioner to X = 0.00 mm.
- Use the fiber mounts for bare PMMA fibers.
- Use the PMMA sections contained within the micropositioner's scope of supply. Use one section for connection of the LED 1 to the micropositioner and the second cable for the connection between the micropositioner and the optical power sensor.
- Secure the fiber by tightening the thumb screws.
- Load the CASSY Lab example Longitudinal.labx.
- Use the Y-micrometer, the Z-height adjustment and the angular positioner to adjust the fiber ends until you obtain the maximum power. The fiber ends should now be in perfect alignment to each other and there should be practically no air gap between them. Right click into the instrument P_{A1}. Activate *Settings sensor input* → 0 ←. The display changes to 0 dB. Start the measurement by pressing *F9*.
- Now adjust the X-micrometer in steps of 100 µm press each time *F9* again.

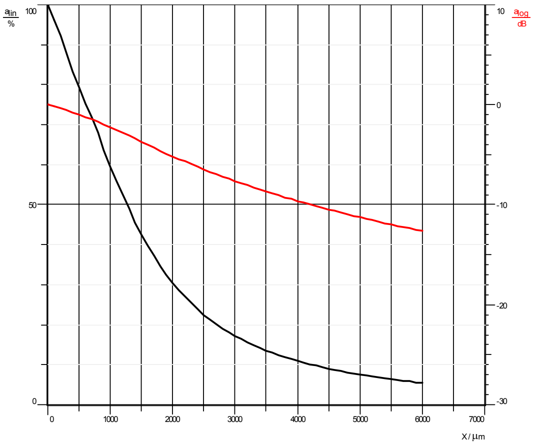
Transversal offset

- Set the X-micrometer of the fiber-micropositioner to X = 0.00 mm. (Starting position for the longitudinal measurement).
- Load the CASSY Lab example Transversal.labx. With the instrument PA1 blinking, reduce the diode current of the LED with the potentiometer V_F, until the display gets stationary.
- Make a right click into the Instrument P_{A1}. Activate *Settings sensor input* → 0 ←. The display changes to 0 dB.
- Set the Y-micrometer of the fiber-micropositioner to Y = 0.00 mm (or to the stop position, depending on the type).
- Start the measurement by pressing *F9*.
- Now adjust the Y-micrometer in steps of 100 µm until you reach Y = 6.00 mm and press each time *F9*.
- Set the X-micrometer of the fiber-micropositioner to X = 2.00 mm.
- Repeat the measurements.

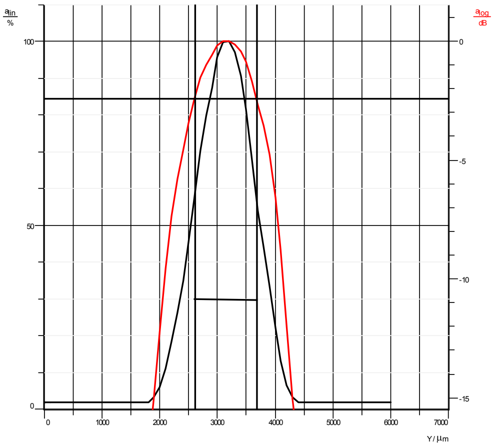
Variant

- Repeat the experiment for LED 2 and LED 3.

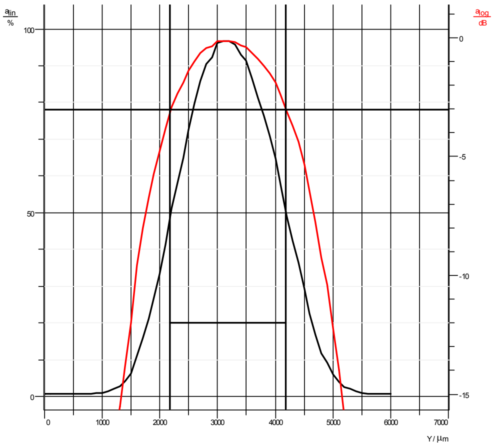
Results



Losses by longitudinal offset
Black: linear representation
Red: logarithmic representation



Transversal coupling losses X = 0.00 mm
3dB-width: 1100 µm
Black: linear representation
Red: logarithmic representation



Transversal coupling losses X = 2.00 mm
3dB-width: 2000 µm
Black: linear representation
Red: logarithmic representation

Summary

Longitudinal offset

PMMA demonstrates a field distribution at the air gap which can be approximated by a falling exponential function. In PMMA cables an air gap of X = 1500 µm generates an attenuation of approx. 3 dB, i.e. already half the optical power is lost. There is no detectable difference between the air-gap attenuation for LED 2 and LED 3.

Transversal offset

The transversal field distribution in front of a multimode fiber shows a dependency which can be approximated with a Gaussian error curve. The Gaussian bell curve is given by:

$$E = e^{-cY^2}$$

Here the factor *c* depends on the longitudinal offset *X* of the two fiber ends. With increasing distance *X* the maxims become flatter and broader.

Reduction of reflexion losses

At every boundary which separates areas with different refractive indices – a part of the incident light is reflected. For the shown case, theory gives the following reflection factor:

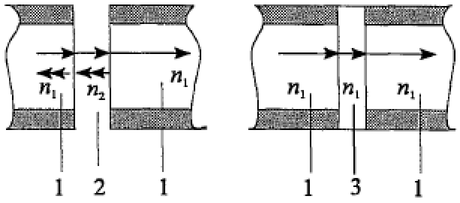
$$r = \frac{n_1 - n_2}{n_1 + n_2}$$

The equation corresponds to the reflection factor on lines. The power P_r reflected at a fiber end is proportional to the square of the reflection factor:

$$P_r = r^2 P_i$$

If for the core glass of the optical fiber we take $n_1 = 1{,}5$ and for n_2 the refractive index for air ($n_2 = 1$) then we obtain:

$r = 0.2$ $r^2 = 4\%$



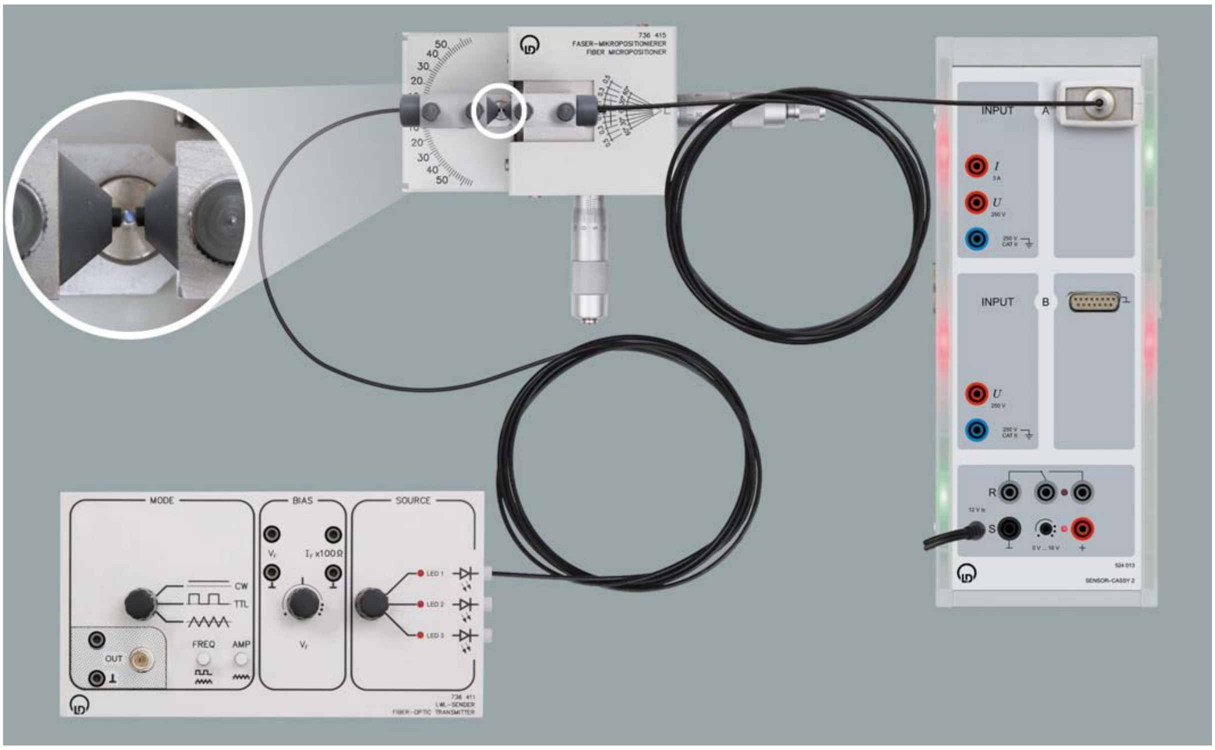
For perpendicularly exiting light approx. 4% of the incident optical power P_i is reflected at every glass-air boundary. For an air-gap plug with 2 glass-air end surfaces this means a reduction in effective power amounting to 8%. This power loss can be avoided by filling the space between the fiber end surfaces with an index paste or an immersion oil. In both cases the space between is adapted to the refractive index of the core glass. Immersion oil is not very practical because it flows out of the air gap. Index pastes attract dirt, collecting dust and other particles. When handled without care the particles trapped in the index paste can scratch the fiber end surfaces (abrasion). In this experiment water is used for index matching, because of its unlimited availability. The refraction index of water is about $n_2 = 1.33$.

Material

1	736 411	Fiber optic transmitter
1	736 415	Fiber micropositioner
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	564 482	Book: Experiments with PMMA fibers
1		PC
		A drop of water

Note: The fiber end surfaces of optical fibers have to be polished for this experiment. If you experiment with unpolished fibers the transmitted power increases up to 100% when the air gap is moistened. Index adaptation only contributes approx. 8...10% to this result, whereas the main improvement is produced by the optical improvement of the end surfaces!

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	fibers		
BIAS	V_F → right	from	CASSY	channel A
SOURCE	LED 1	micropositioner		

- Assemble the experiment as shown. Take the two optical fibers with length 1 m from the accessory of the micropositioner (with polished surfaces, see note above).
- Use the mounts for bare PMMA fibers in the fiber micropositioner.
- Set the X-micrometer of the fiber-micropositioner to X = 0.00 mm.
- Insert the two optical fibers into the mounts, until the fiber ends get into contact.
- Separate the two fiber ends by setting the X-micrometer of the fiber-micropositioner to X = 0.50 mm
- Load the CASSY Lab example ReflexionLoss.labx.
- Use the Y-micrometer, the Z-height adjustment and the angular positioner to adjust the fiber ends until you obtain the maximum power. The fiber ends should now be in perfect alignment to each other with an air gap X = 0.50 mm between them.

- Make a right click into the instrument “Optical Power P_{A1}” to activate *Settings.* Click on: → 0 ←. Reduce V_F if the display is blinking.
- The displays on the attenuation instruments G and g change to 100 % respectively to 0.0 dB.
- Apply a drop of water between the fiber-ends. See enlarged part of experiment set up.
- Record the linear and logarithmic attenuation G and g in the table.
- Dry the air gap between the fiber ends.
- Repeat the experiment for LED 2 and LED 3.
- Give an interpretation

Reduction of the reflection losses

SOURCE	**G/%**	**g**
LED 1		
LED 2		
LED 3		

Results

- Index matching results in a power gain due to the bridging of small air gaps. If in the experiment the air gap is made too large, then additional losses arise, which rapidly become even greater on account of the large NA (numerical aperture) of PMMA optical fibers.
- With two glass-air junctions we could expect a linear increase from G = 100% G = 108% (g = +0.33 dB).
- Deviations from that theoretical value are due to the huge air gap (0.5 mm) which provokes a strong spillover of light from the emitting fiber. With increasing distance between the two fibers, an even smaller amount of light can be coupled into the receiving fiber (under dry conditions). Thus the result after index matching is emphasized.
- Each plug connection adds approximately 1 dB losses into the optical power budget. In the case of scratched fiber ends the power gain appears to be greater (effect of coarseness).
- The reduction in reflection losses is relatively constant with the wavelength of the light.

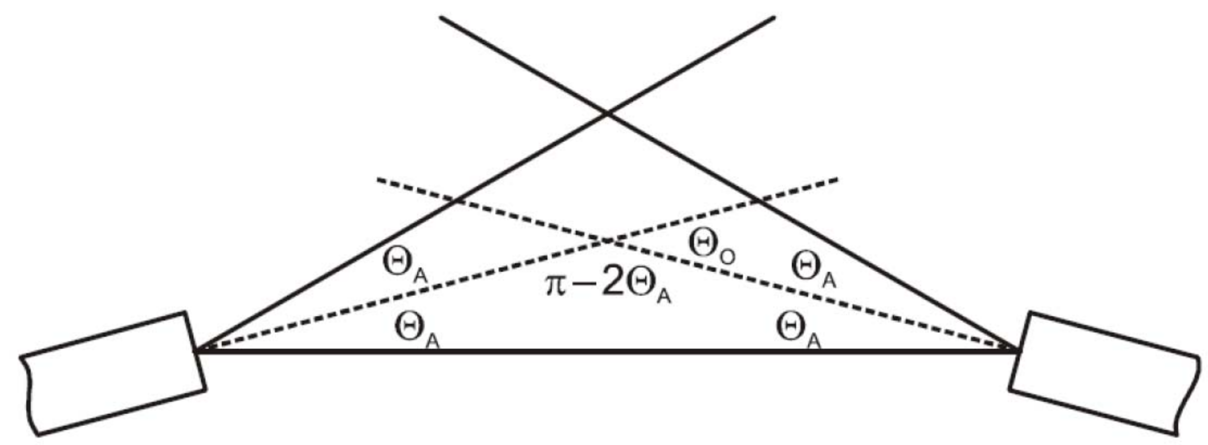
Reduction of the reflexion losses

SOURCE	G/%	g
LED 1	112	+0.5 dB
LED 2	115	+0.6 dB
LED 3	111	+0.5 dB

Numerical aperture

Theory

The numerical aperture (NA) is an important parameter in fiber optics. The greater the NA, the greater the coupling effectiveness, i.e. the more light incident at an angle can be coupled into the fiber. Also the losses resulting from bends decrease with increasing numerical aperture. In the case of short fiber lengths a portion of the light is also propagated in the cladding or in higher modes. Due to the higher attenuation for these modes the numerical aperture declines with increasing fiber length and reaches its constant value only after a certain fiber length.

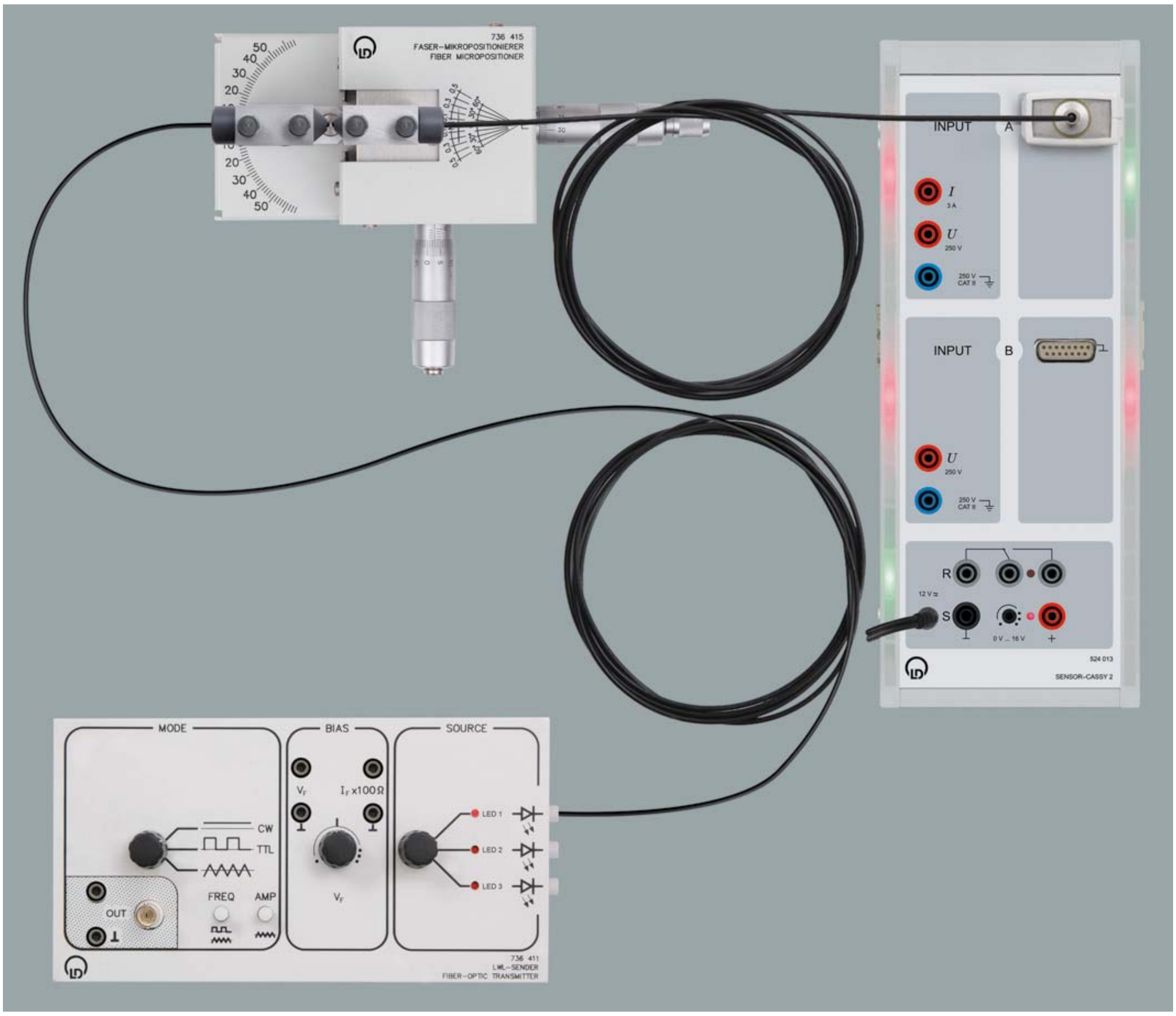


Measurement of the acceptance angle θ_A: The axes of the fibers intercept at the half aperture angle θ_0.

Material

1	736 411	Fiber optic transmitter
1	736 415	Fiber-micropositioner
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		**Fiber**	**Optical power sensor S**	
MODE	CW	Fibers		
BIAS	V_F → right	from	CASSY	channel A
SOURCE	LED 1	micropositioner		

- Set up the shown experiment.
- Load the CASSY Lab example NumAp.labx.
- Start the measurement by pressing *F9.*

- In case the display is blinking, turn the potentiometer V_F back. Right click into the instrument P_{A1}. Activate *settings sensor input* → 0 ←. The display changes to 0 dB.
- The determination of the NA with the aid of the fiber micropositioner 736 415, is based on the measurement of the acceptance angle θ_A. This is half the aperture angle θ_0 of the cone within which light can penetrate into the fiber. The aperture angle θ_0 is directly related to the acceptance angle and the *NA*.

$$\Theta_A = \frac{1}{2}\Theta_0$$

$$NA = \sin\theta_A = \sqrt{(n_1^2 - n_2^2)}$$

- The aperture angle θ_0 can be read off directly from the angular scale of the micropositioner. Use the bare PMMA fiber sections and the corresponding fiber mounts included with the fiber micropositioner.
- Insert the bare ends into the fiber mounts of the micropositioner. The fiber ends should be aligned symmetrically to the axis of rotation. The space between the fiber-ends amounts to approx. 2 mm.
- Align the angular positioner to 0°. Use the Y-manipulator to calibrate to minimum the transversal offset. This gives the maximum optical power. Proceed in the same fashion to calibrate the Z-axis for the height adjustment using the thumb screw.
- Now carefully turn the angular positioner in both directions. Closely observe the receiving signal. Note down the angles θ_{01} and θ_{02} at which the optical power has dropped below –15 dB. Calculate the mean acceptance angle and the NA.

Determination of the NA

SOURCE	θ_{01}/GRD	θ_{02}/GRD	θ_A/GRD	NA
LED 1				
LED 2				
LED 3				

Note

- You can roughly determine the acceptance angle θ_A and the NA from the aperture angle θ_0 of the beam cone by holding the fiber end surfaces to the scale of the micropositioner. Protect the (weak) light cone from the effects of outside light with your hand.

Results

Summary

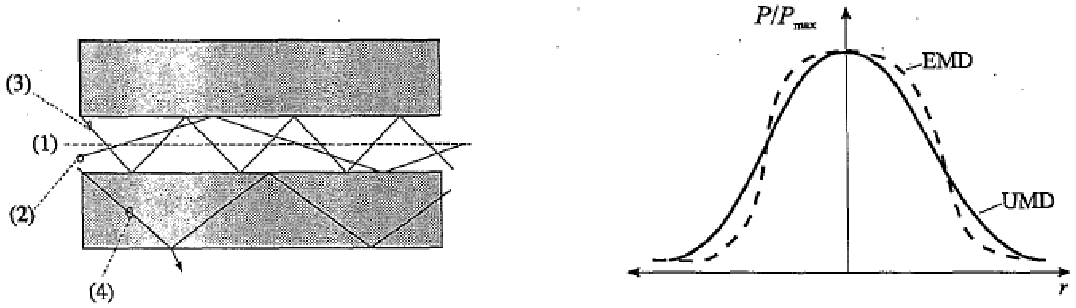
Coupling light into the fiber after falling below the acceptance angle is performed gradually, not abruptly. The reason for this is the beam characteristic of the fiber end. Therefore when determining the acceptance angle θ_A you need a little practice to detect this gradual transition.

Determination of the NA

SOURCE	θ_{01}/GRD	θ_{02}/GRD	θ_A/GRD	NA
LED 1	50	54	26	0.44
LED 2	50	54	26	0.44
LED 3	50	54	26	0.44

Suppression of undesired modes

Theory



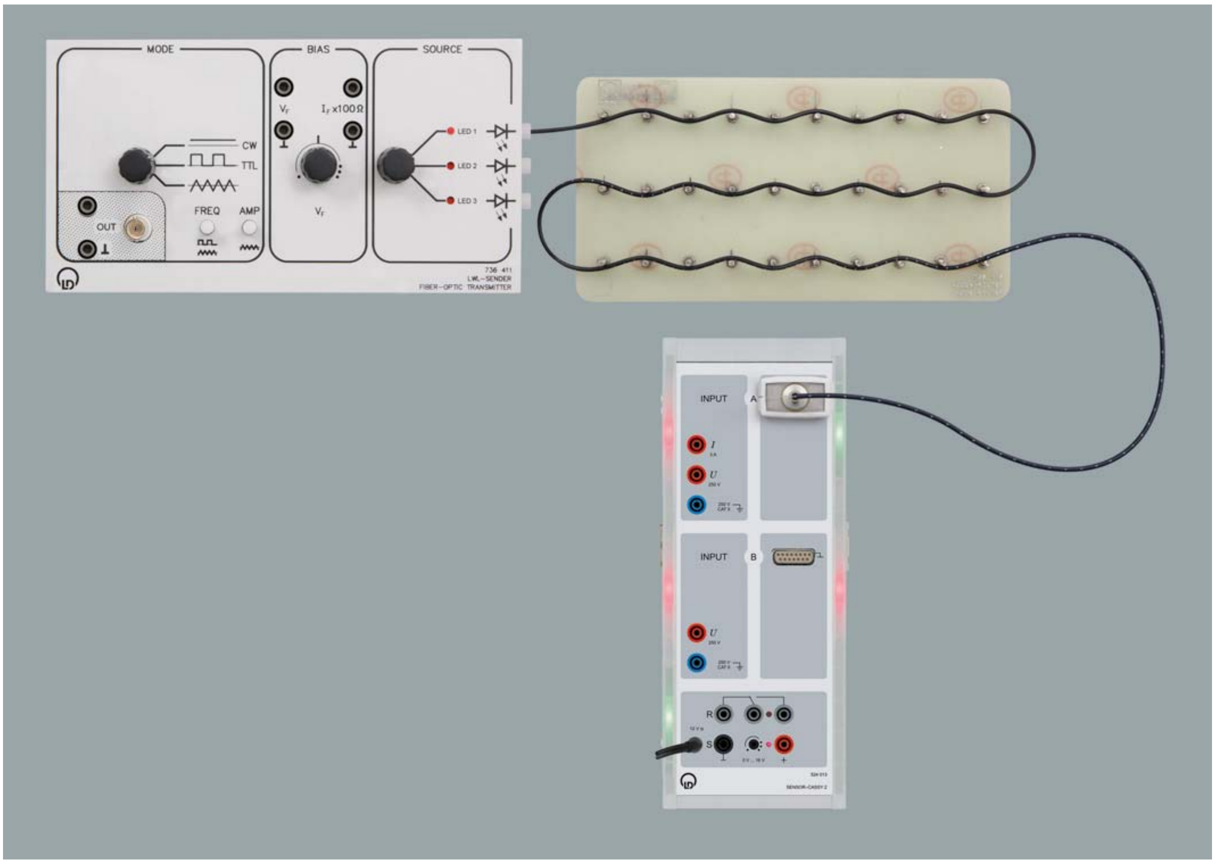
In a step index fiber only light beams can propagate which strike the fiber end at under a certain angle. Incident light at unacceptable angle is cancelled out due to destructive interference caused by repeated reflections along its path through the fiber. Beams propagating at accepted angles are called modes. When a beam is launched at the fiber end, this can result in so-called cladding modes. These beams are sharply reflected around the fiber axis. Although cladding modes are allowed, they propagate - as their name suggests - in the optical cladding of the fiber. Because these normally have a higher attenuation than modes propagating in the core glass the power of the cladding modes rapidly decreases with increasing fiber length. Furthermore cladding modes penetrate into the outer jacket. Under uniform illumination of the fiber end all accepted modes are excited (UMD).

Due to the more severe attenuation of the cladding modes, the uniform distribution decreases with increasing fiber length. The light is propagated more and more in modes of attenuation lower order. The attenuation (a/dBkm^{-1}) reaches a constant value. In the fiber an equilibrium mode distribution settles in (EMD). Cladding modes have to be avoided at high modulation frequencies and short fiber segment lengths due to mode dispersion arising. They also pose a problem when performing attenuation measurements. To achieve mode equilibrium and to suppress disturbing cladding modes so-called mode filters (mode strippers) are used. These increase the losses for higher modes by causing artificially induced bend attenuation. Thus EMD distribution can be produced even on short fiber lengths.

Material

1	736 411	Fiber optic transmitter
1	736 416	Mode filter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW			
BIAS	V_F → right	Fiber from	CASSY	channel A
SOURCE	LED 1	micropositioner		

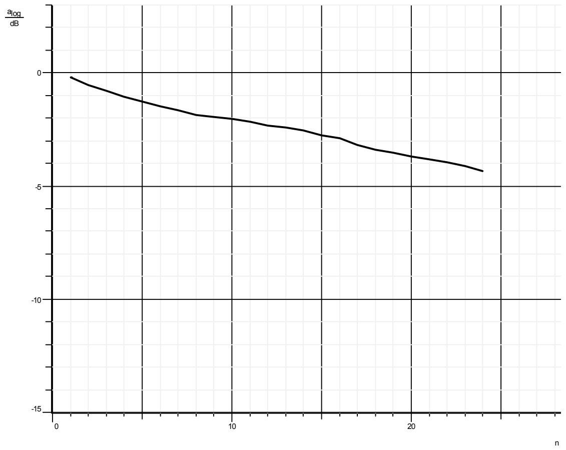
- Set up the shown experiment
- Guide the fiber without strong bendings from the LED to the optical power meter.
- Load the CASSY Lab example ModeAtt.labx.
- Make a right click into Instrument P_{A1}. Activate *settings sensor input* → 0 ←. The display changes to 0 dB.
- Start the measurement by pressing *F9.*
- Now lead the fiber across the mode filter. Measure the optical attenuation in function of the number of bendings *n*. Press each time *F9*.
- Display graphically the bending attenuation as a function of bendings *n*.

Number of bendings *n*	**a_{log} / dB**
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	
21	
22	
23	
24	

Variant

- Repeat the experiment for different fiber lengths and at different wavelengths.

Results



Number of bendings *n*	a_{log} / dB
1	-0.2
2	-0.5
3	-0.8
4	-1.0
5	-1.3
6	-1.5
7	-1.7
8	-1.8
9	-2.0
10	-2.0
11	-2.1
12	-2.3
13	-2.4
14	-2.5
15	-2.7
16	-2.9
17	-3.2
18	-3.4
19	-3.5
20	-3.7
21	-3.8
22	-4.0
23	-4.1
24	-4.3

Summary

With PMMA cables a large portion of the optical power is propagated in modes of higher order or in cladding modes. Therefore this type of optical fiber responds very strongly to the use of mode filters in the transmission link. In PMMA fibers many cladding modes occur, mode equilibrium is practically impossible to achieve. The effect of bending attenuation in PMMA fibers is not completely reversible. The thick PMMA cable shows slight time-invariable behavior when the bends have been removed. This can be attributed to link processes in the extended core of the fiber (recovery effect).

Worksheets

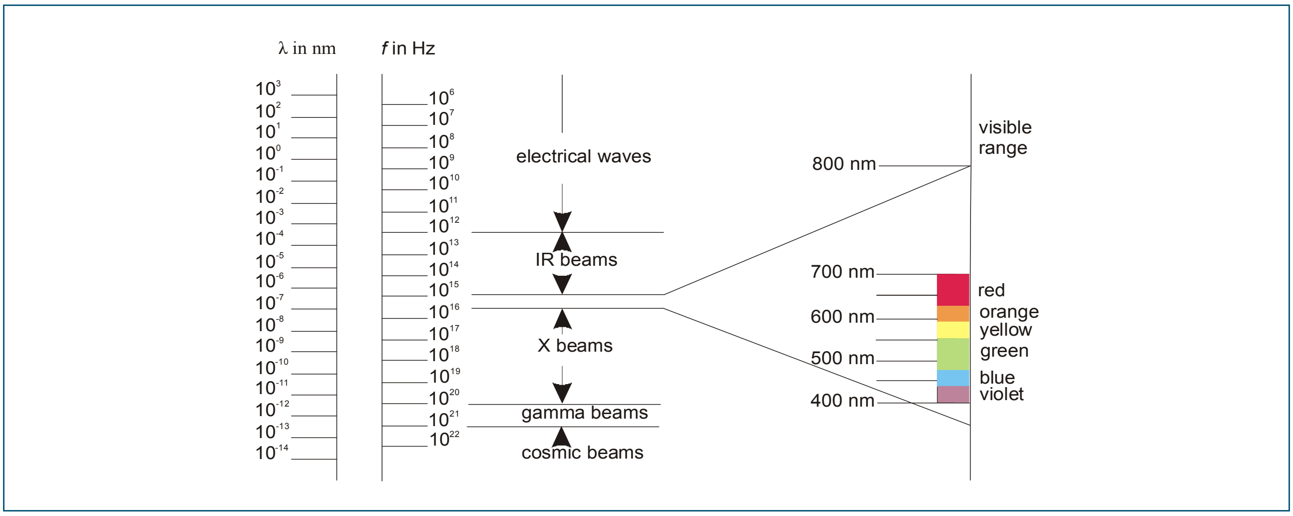
Theory

Physical principles

The electromagnetic spectrum

For the transmission of messages, the propagation of electromagnetic waves in a transmission medium is of fundamental importance. The medium does not have to be a metalic 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 short-wave cosmic beams. For optical communications technology only a very small range is suitable, namely infrared (IR) and visible (VIS), as well as the ultraviolet (UV) part of the electro-magnetic spectrum. 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 beams while the IR beams 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*:

$$\lambda = \frac{c_0}{f}$$



Where c_0 stands for: $c_0 = 3 \cdot 10^8$ 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.

Beam optics

Light propagation in a multimode optical waveguide can be explained using the laws of geometrical optics. Light serve as a simple theoretical concept (model). 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 waveguide is based on the laws of refraction and reflection. As a rule both processes occur when a beam incidents a dielectric surface. If a beam strikes the surface of two different substances with different refractive indexes *n*, then the following holds true according to the law of reflection:

$$\alpha = \alpha'$$

The angle of incidence α and angle of reflection α' are in the same plane.

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2}$$

The ratio of light velocity c_0 in 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.

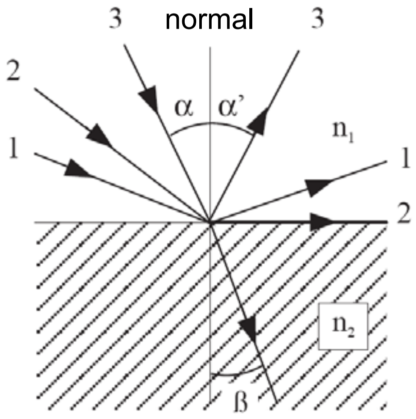
$$c = \frac{c_0}{n}$$

Using the equation we obtain:

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1}$$

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. 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:

$$\sin\alpha_c = \frac{n_2}{n_1}$$



Reflection and refraction

Thus, if the angle of incidence surpasses the critical angle α_c, no refraction can occur and the beams are totally reflected at the surface. This phenomenon is called total reflection. It only takes place during the transition from an optically denser medium to an optically less dense one.

Fiber optic telecommunications systems

Design of optical waveguides

Total reflection is exploited as the guiding mechanism in optical waveguides (multimode fibers). For this reason the optical wave guide consists of a cylindrical core and a concentric cladding surrounding. Here the refractive index n_1 in core glass is somewhat larger than that of refractive index n_2 in the glass cladding. All light beams which do not deviate more than (90°– α_c) from axial direction of the optical waveguide are guided inside the glass core. In order to launch 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 (Θ = angle between beam and fiber axis):

$$\frac{\sin\theta}{\sin(90^\circ-\alpha)}=\frac{n_1}{n_0}$$

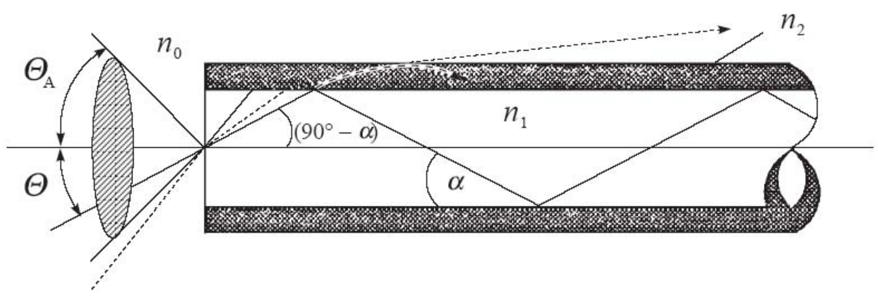
From this it follows with n_0 = 1:

$$\sin\theta = n_1\cos\alpha = n_1\sqrt{(1-\sin^2\alpha)}$$

The largest coupling angle Θ_A is called the acceptance angle of the fiber optic waveguide 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 waveguide:

$$NA=\sin\theta_A=\sqrt{(n_1^2-n_2^2)}$$

This numerical aperture *NA* B is an important quantity for coupling light into a fiber optic waveguide. The greater the numerical aperture of an optical fiber, the more light can be coupled, but this also introduce more propagation time differences between higher order modes.



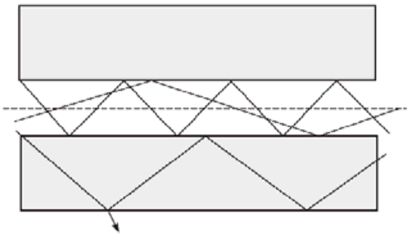
Light guided through a fiber optic waveguide

Fiber optic profiles

If we consider the refractive index *n* of a fiber optic waveguide 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 (SI)
- Graded index profile (GI)

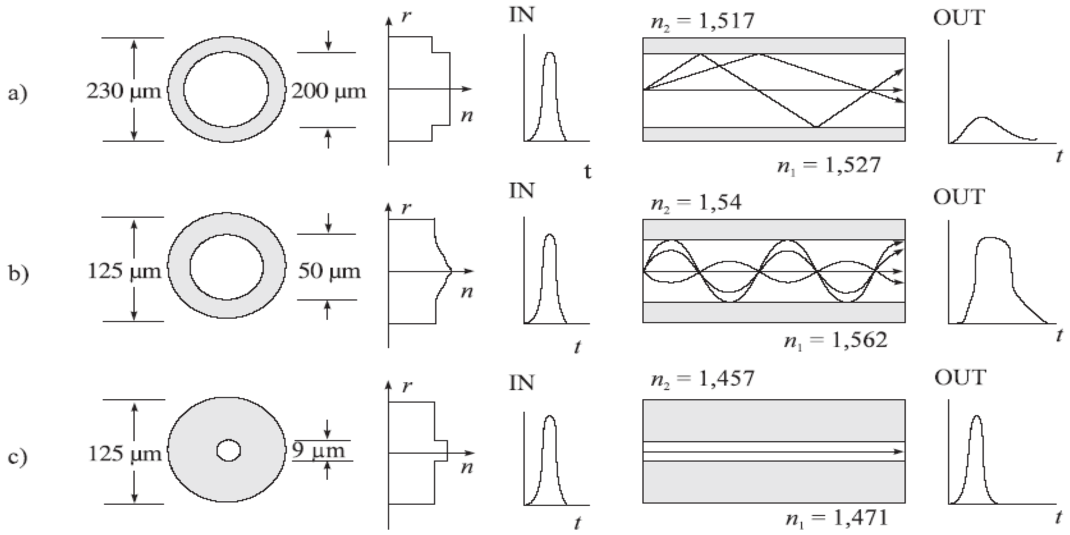
The step-index profile is characterized by a constant refractive index n_1 within the core and a sharp drop to n_2 ($n_1 > n_2$) at the boundary between the core and cladding.



Mode distribution in a step index fiber

The figure shows that beams guided in a flatter fashion travel a shorter distance than the ones traveling at a steep angle because the latter types are reflected more frequently. This is referred to as modes of higher order (multiple zigzag course) and accordingly modes of a lower order (few reflections). Modes are possible propagation paths in a fiber optic waveguide. The existence of mode of various orders leads to complications in signal transmission. A light pulse of short duration may be 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 step index fiber is not suited for the transmission of broad band signals. The graded-index profile provides assistance here. In contrast to the step-index profile the light beams in a fiber optic waveguide do not propagate in zigzag fashion. The refraction index profile of a graded index fiber changes continuously over the radius of the fiber. The guiding mechanism of the graded index 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 beams are constantly subjected to refraction. The propagation direction is constantly changing running in wavelike paths along the axis of the fiber. Steep beams oscillating around the axis always have farther to travel than the light beams traveling along the axis. However, due to the lower refractive index outside the axis of the fiber these beams travel at faster speed, through which the longer distance is made up for in time. As a result, the differences in propagation time for the individual beams disappear almost completely. Modal dispersion is only slight. However 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 µm – 10 µm. Only one single mode can propagate along the core thus eliminating the possibility of any propagation time difference (no modal dispersion). The following figure provides an overview concerning the dimensions, refractive index profiles and some additional characteristic variables.

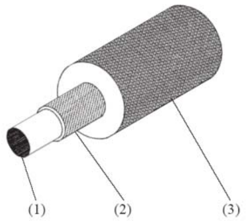
Common types of fiber optic waveguides



a:	step index (SI)	multimode	diameter core/cladding	230/200
b:	graded index (GI)	multimode	diameter core/cladding	50/125
c:	step index (SI)	monomode	diameter core/cladding	9/125

Fiber production, material selection

Plastic and silica glass have gradually become predominant for the production of fiber optic waveguides. So-called all plastic waveguides are used for simple communication systems. The most common fiber type consists of an approx. 970 µm thick core of poly-methyl-methaacrylat (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 left (up to approx. 100 m). The figure shows the schematic design of a PMMA fiber. The *NA* amounts to 0.47 which corresponds to an acceptance angle of 28°. For high traffic transmission left (e.g. cable networks and telecommunication networks operated by telephone and communications companies) 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.



Design of a PMMA fiber

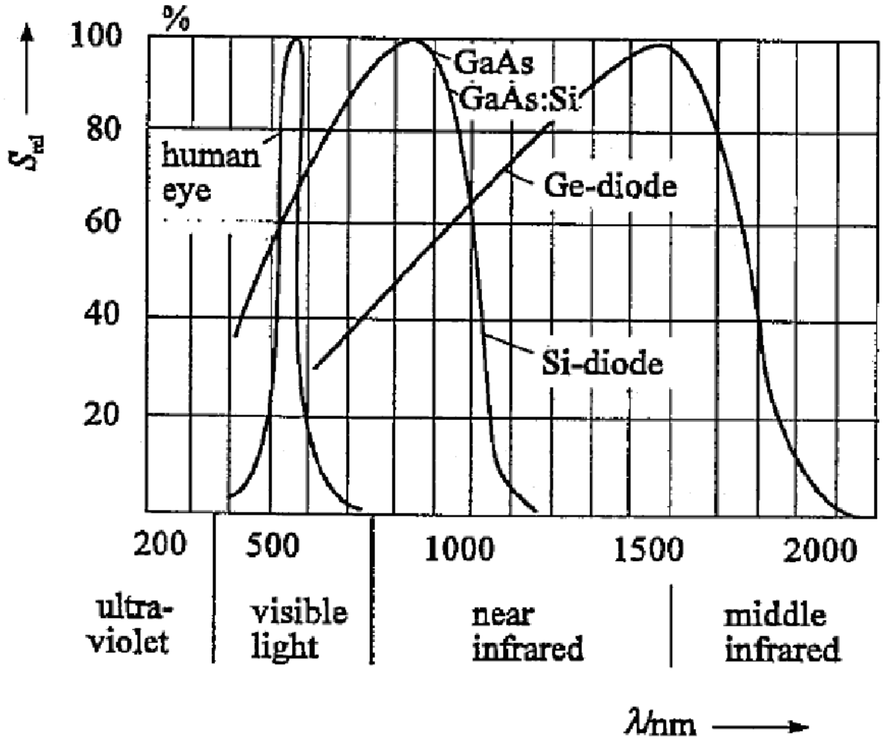
1: core, diameter:	970 µm, n_1 = 1.492
2: optical cladding:	15 µm, n_2 = 1.417
3: protective jacket, diameter:	2.2 mm

Light sources

In optical communications technology LED and solid-state lasers (LD) are primarily used as light sources. Taken from the electrical point-of-view these semiconductor light sources are considered PN diodes, which are operated in the forward direction. The effect of spontaneous recombination is exploited in LED sources.

Detectors

The opto-electrical conversion brought about by the absorption of the light beam takes place in the photodiode. In actual practice the spectral sensitivity S_{rel} is important. This indicates which current *I*p is obtained at the photodiode for prespecified, incident light power P_2. Typical values for silicon diodes for a wavelength of 850 nm are at about S_{rel} = 0,5 A/W. The figure 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.



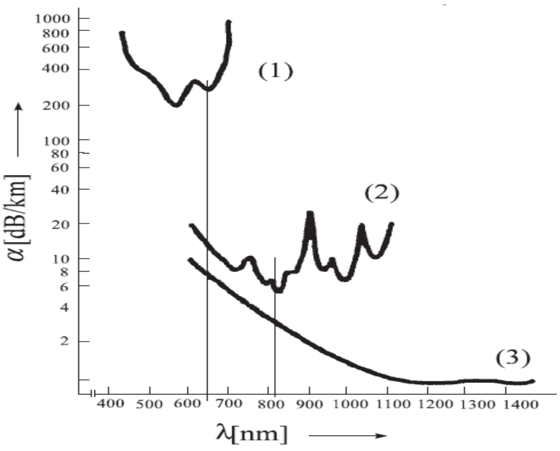
Attenuation

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 connectors
- Material attenuation of the fiber optic waveguide

The attenuation of the fiber optic waveguide depends on the wavelength, while, the attenuation of the connectors is 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 the light no longer arrives at the aperture angle opposite fiber and is thus lost for signal transmission. Material attenuation of the fiber optic waveguide is caused by:

- Light scattering
- Light absorption
- Beam losses related to the guidance of the waveguide.



Fiber optic attenuation

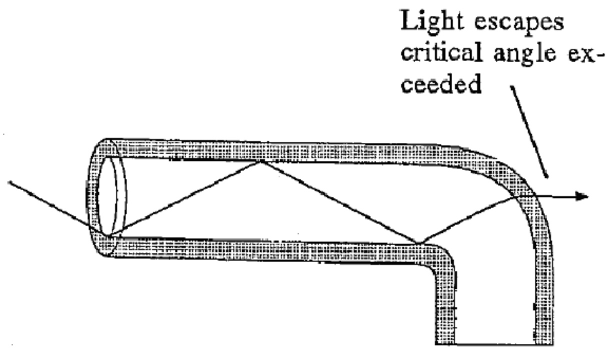
(1) APF Cable (all plastic fiber e.g. PMMA

(2) PCF plastic cladding fiber

(3) Glass fiber

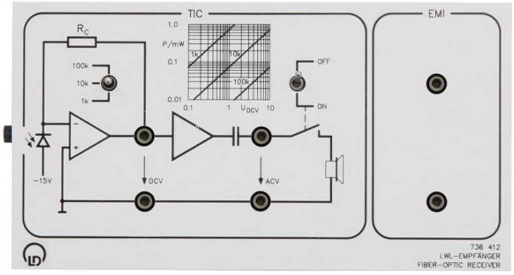
Linear scattering (Rayleigh scattering) is due to statistical fluctuations in the refractive index. These result from random molecular structures in the waveguide material. The refractive index varies in sections which are small in comparison with the wavelength of light. Absorption means the conversion of beam energy into heat when impinging on impurities (atoms or molecules). The severity of the effect depends on the wavelength and spans the entire range, from ultraviolet to infrared.

In addition to the scattering and absorption there also exists beam losses through conversion from guided 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.



However, due to the relatively high attenuation in the cladding material mantle modes are incapable of propagation even without a bent optical waveguide. 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 1300 nm (2nd window) for glass optical fibers.

Training system



736 411 Fiber optic transmitter

Three integrated, LED for experiments at various wavelengths. Potentiometer for the continuous setting of the bias voltage for recording characteristics. 4-mm sockets for the connection of the Sensor-CASSY interface. Internal signal generator (triangular/ square-wave) with BNC/4-mm output sockets for experiments involving modulation. **Note:** LEDs are subject to change in production. Thus the wavelengths of the LEDs within the Fiber optic transmitter can deviate from solutions given in the text.

736 412 Fiber optic receiver

Discretely assembled transimpedance amplifier with switchable conversion resistors. Separate DC and AC output. The DC output permits investigation of the dark current. With the AC output the advantages of modulation can be demonstrated. Built-in piezo loudspeaker.

736 421 Set of optical fibers and accessories

Set of PMMA fiber-optic cables with step index profile and 980/1000 µm core/cladding diameter. Plastic cladding with 2.2 mm external diameter.

1 Optical fiber, length 50 m
1 Optical fiber, length 20 m
1 Optical fiber, length 10 m
1 Optical fiber, length 5 m
1 Plastic optical fiber, transparent, length 10 m
  diameter 1 mm with connection piece 2.2 mm
1 Plexiglas directional coupler
1 Polishing tool
1 Abrasive cloth

736 429 Fiber optic microscope

The light is switched on, when the microscope is opened. In order to spare the batteries close the microscope after use.

Loose fiber adapter for checking the fiber end surfaces of bare PMMA sections. Only tighten when necessary.

LED characteristics

Theory

The diode characteristic in flow direction ($U_F > 0$) is described by the differential resistance r_F.

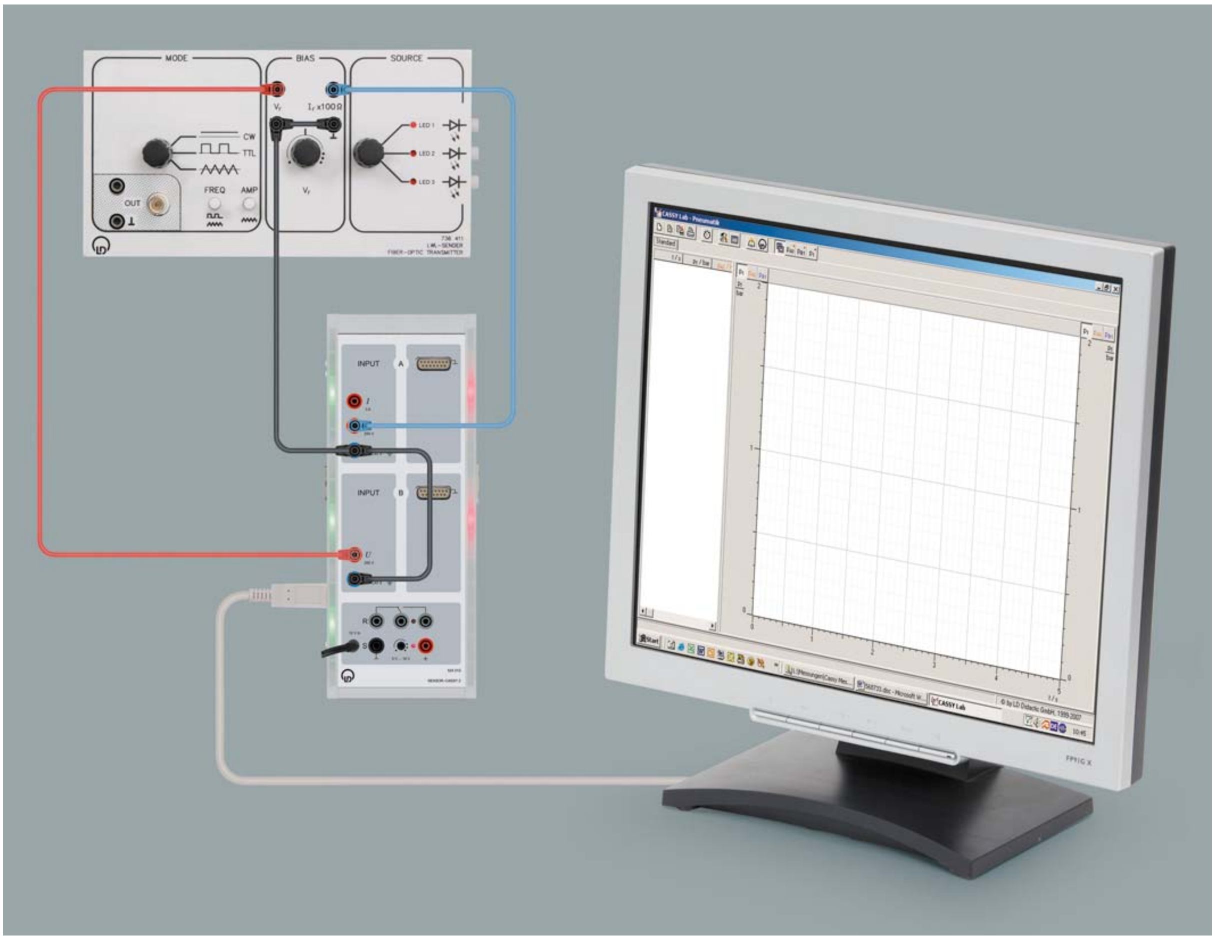
$$r_F = \frac{\Delta U_F}{\Delta I_F} \Delta$$

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 techniques with their attendant demands on linearity.

Material

1	736 411	Fiber optic transmitter
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	500 604	Safety connection lead 10 cm, black
2	500 644	Safety connection lead 100 cm, black
1	500 642	Safety connection lead 100 cm, blue
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	CW		R_C	---
BIAS	V_F → left	---	Output	---
SOURCE	LED 1 / 2 / 3			

Current-voltage characteristic

- Set up the shown experiment.
- Load the CASSY Lab example LEDCharacteristic.labs.
- Start the measurement by pressing *F9*.
- Record the current-voltage characteristic of the emitting LED in the forward direction, by slowly turning the potentiometer V_F to the right. Note: At the socket I_Fx100 Ω a voltage across an internal 100 Ohm resistor is measured. The diode current is thus converted into a voltage, which is easier to measure.
- Reaching the top right position of the potentiometer press *F9* again.
- Draw a tangent which intersects with the current-voltage characteristic. To do this make a right mouse click into the diagram *Fit Function / Best-fit Straight Line*. Mark the measurement values in the steep part of the characteristic by pressing the left mouse button. The parameter *A* is the inverse value of the differential resistance r_F:

$$r_F = \frac{1}{A}$$

Discuss the characteristic Determine the differential resistance r_F. What can be concluded about the differential resistance of the LED?

SOURCE	A/mAV^{-1}	r_F/Ω	V_S/V
LED 1			
LED 2			
LED 3			

- Repeat the recording and the evaluation of the characteristic for the LED 2 and LED 3.

Current-Power characteristic

- Load the CASSY Lab example LEDInputPower.labs.
- Start the measurement by pressing *F9*.
- Record the current-power characteristic of the emitting LED in forward direction by slowly turning the potentiometer VF to the right.
- Reaching the top right position press *F9* again.
- Display the current-power-characteristics in a common diagram.

Results

LED characteristics
blue: $V_s = 1.2$ V
red: $V_s = 1.5$ V
black: $V_s = 1.7$ V

Electrical input power of the LED

Summary

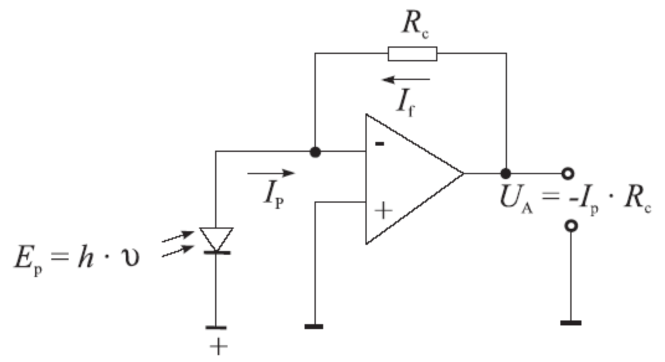
The LED practically blocks until the threshold voltage V_S are reached. Only after a further rise in the diode forward voltage U_F does the current increase steeply. If a tangent is applied to the steep part of the characteristic, than we obtain the threshold voltage at the point where the tangent intersects the voltage axis. The values obtained with CASSY Lab can be taken from the adjoining table.

SOURCE	A/mAV$^-$	r_F/Ω	V_S/V
LED 1			
LED 2			
LED 3			

Note: Changes in electrical characteristics can arise due to modifications in the production of the LEDs.

The transimpedance amplifier

Theory



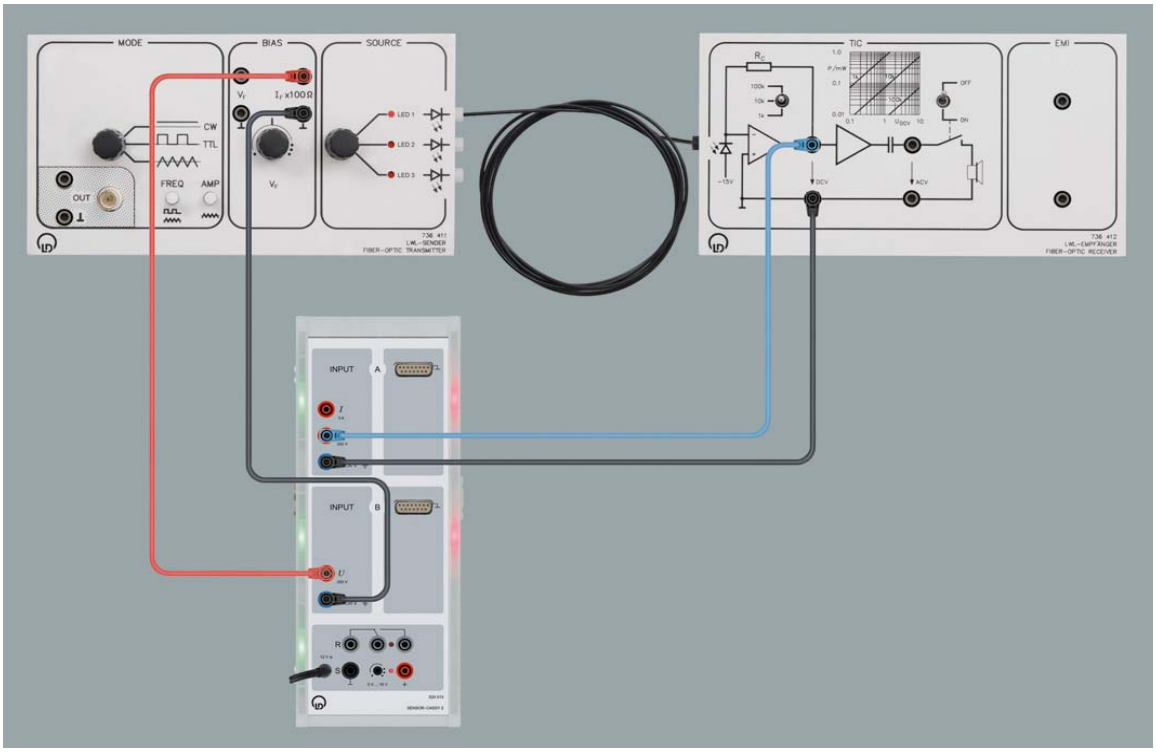
Transimpedance amplifier

In the fiber optic receiver 736 412 a PIN photodiode is used as the receiving element. The photodiode can be represented in the equivalent circuit diagram as a light-controlled current source. For this, it is biased in the blocking direction. Its reverse current I_P is then proportional to the intensity of the incident light. Using the shown circuit, the highly resistive current source of the photodiode is converted into a low resistance voltage source. If an ideal operational amplifier is assumed, the entire photocurrent I_P flows off across the conversion resistor designated R_C. Since the positive input of the op-amp is connected with respect to earth potential the output voltage is set to a value which is given by $-I_P*R_C$. Because the conversion factor between the input variable (photo current I_P) and output variable V_A has the dimension of an impedance, the circuit is called a transimpedance circuit. Due to the linearity existing between the incident light power and the output voltage, the transimpedance circuit can be employed for relative power measurements.

Material

1	736 411	Fiber optic transmitter
1	736 412	Fiber optic receiver
1	736 421	Set of fiber-optic waveguides and accessories
2	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
2	500 644	Safety connection lead 100 cm, black
1	500 642	Safety connection lead 100 cm, blue
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	CW		R_C	100 k
BIAS	V_F → left	10 m	Output	DCV
SOURCE	LED 1 / 2 / 3			

- Set up the shown experiment.
- Put the fiber at both endings firmly into the connectors.
- Load the CASSY Lab exampleTransimp.labs.
- Start the measurement by pressing *F9.*
- Slowly enhance the LED bias voltage (V_F) at the fiber optic transmitter.
- Reaching the top right position press *F9* again.
- Switch R_C to 10 K and 1 K. What do you observe?
- Remove the fiber from the receiver. Cover the photodiode with your finger. Enhance the sensitivity of the multimeters to 100 mV. Vary R_C. What do you observe?
- Connect the fiber with LED 2 at the fiber optic transmitter and switch SOURCE to LED 2.
- Start a new measurement by pressing *F4* and *F9.*
- Successively take the characteristic for LED 2 and R_C =1/10/100 k.
- Finally press *F9* again.
- Connect the fiber with LED 3 at the fiber optic transmitter and switch SOURCE to LED 3.

Results

LED 1: (e.g. λ = 665 nm)

Interpretation:

LED 2: (e.g. λ = 470 nm)

LED 3: (e.g. λ = 950 nm)

Interpretation:

Note: The wavelength of the light emitted by the transmitter LEDs may change due to the current availability of electronic components. The results of the experiments are not significantly affected.

Summary

Apart from the DC output due to dark current, there is a parasitic DC-voltage from the offset of the op-amp. The offset voltage is not influenced by R_C. The dark current and thus its parasitic voltage are very small. To reduce the influence of offset and dark current it is common use to modulate the light signal. The transimpedance amplifier needs an AC coupling for this.

Optical power of the emitting diodes

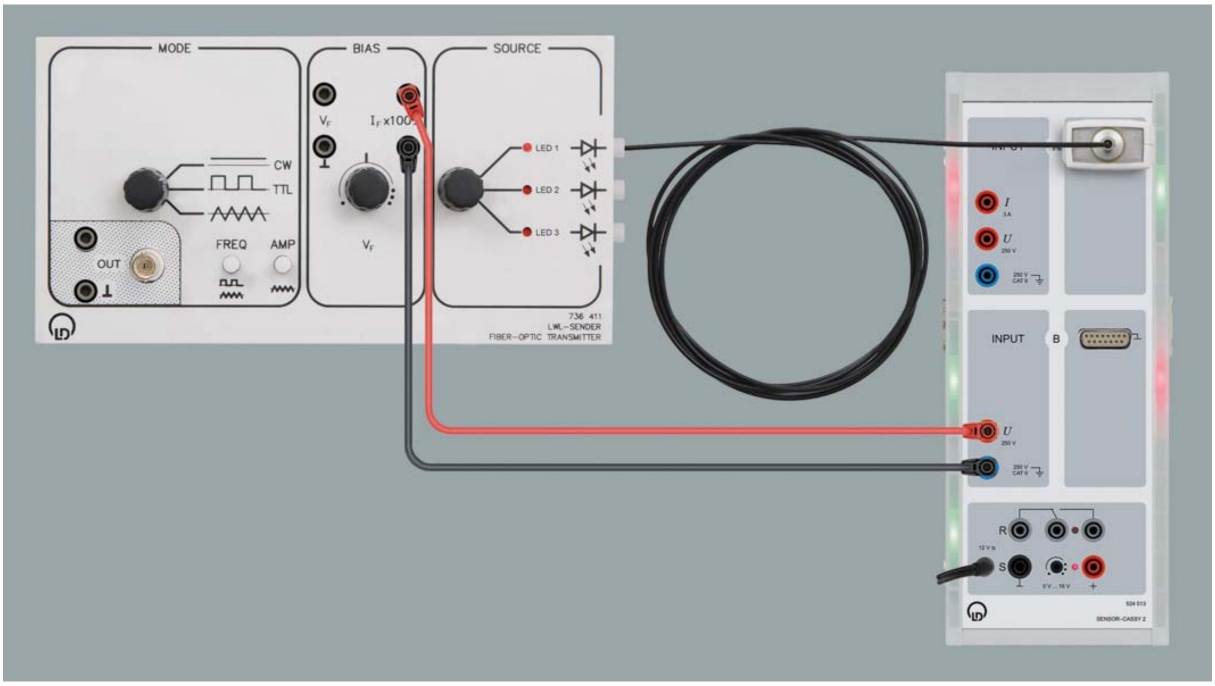
Theory

In this experiment the optical power P_2 emitted by the LED is determined. Since we already know from the last experiment the electrical power consumption P_1 of the LED as a function of the forward current the electro-optical efficiency η can be calculated as the quotient P_2/P_1 and represented as a function of the forward bias current I_F. An optical power meter is needed to measure the absolute optical power P_2. This is normally calibrated in dBm and gives a direct optical power reading.

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12 VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		**Fiber**	**Optical power sensor S**	
MODE	CW			
BIAS	V_F → left	5 m	CASSY	channel A
SOURCE	LED 1			

Recording the power characteristic

- Set up the shown experiment.
- Put the fiber at both ends firmly into the connectors.
- Load the CASSY Lab example OpticPower.labs.
- Start the measurement by pressing *F9.*
- Turn the potentiometer V_F slowly to the right.
- Reaching the top right position, press *F9* again.
- Repeat the measurements for LED 2 and LED 3.

Determining the electro-optical efficiency

- Determine for each LED the forward voltage U_F, which comes with the forward bias currents I_F = 10/20/30 mA.
- Determine the electrical input power $P_1 = I_F \cdot U_F$.
- Calculate the electro-optical efficiency of the total transmission line $\eta = P_2/P_1$.
- Take the values for P_1 and P_2 from the CASSY tables.
- Note all values into the table.

Electro-optical efficiency

	I_F = 10 mA			I_F = 20 mA			I_F = 30 mA		
SOURCE	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**
LED 1									
LED 2									
LED 3									

Results

Optical power of LED 1

Optical power of LED 2

Optical power of LED 3

Interpretation

Electro-optical efficiency

	I_F = 10 mA			I_F = 20 mA			I_F = 30 mA		
SOURCE	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**	**P_1/mW**	**P_2/µW**	**η/%**
LED 1									
LED 2									
LED 3									

Summary

The electro-optical efficiency η represents the ratio of optical output power P_2 to the supplied electrical power P_1. It is a measure of the power dissipation along the entire transmission link

- Crystal → LED housing
- LED housing → air
- Air → fiber optic waveguide

The total efficiency lies in the maximum range of around 1 %. The coupling losses of the plugs also reduce the efficiency of the entire link. The electro-optical efficiency of an LED lies at approximately η = 3...4%. It is that low because the beam generated remains in the LED due to absorption and reflection. The curve of the PI- characteristic is nearly linear, i.e. a continuous change in current results in a proportional change in optical power. If the current changes sinusoidal or square-wave shaped through modulation the consequence is a corresponding change in optical power. Therefore the LED is used particularly for signal transmissions in which it is essential to keep the shape of the transmitted signal. If one were to continue increasing the current I_F then we would eventually see saturation in the optical power characteristic. The reason for this is the power dissipation in the LED caused by higher currents. A portion of the electrical power supplied is converted into heat and not into light, power losses climb, the efficiency falls. In order to keep such a thermal excess to a minimum, efforts have to be made to ensure good cooling.

Notes

Deviations from the numerical values are possible because:

- Different power of the LED
- Different sensibility of the photodiode
- Conditions of the fiber ends (crashed, polished)

Absolute values are only meant as a guideline.

Light guidance by optical waveguides

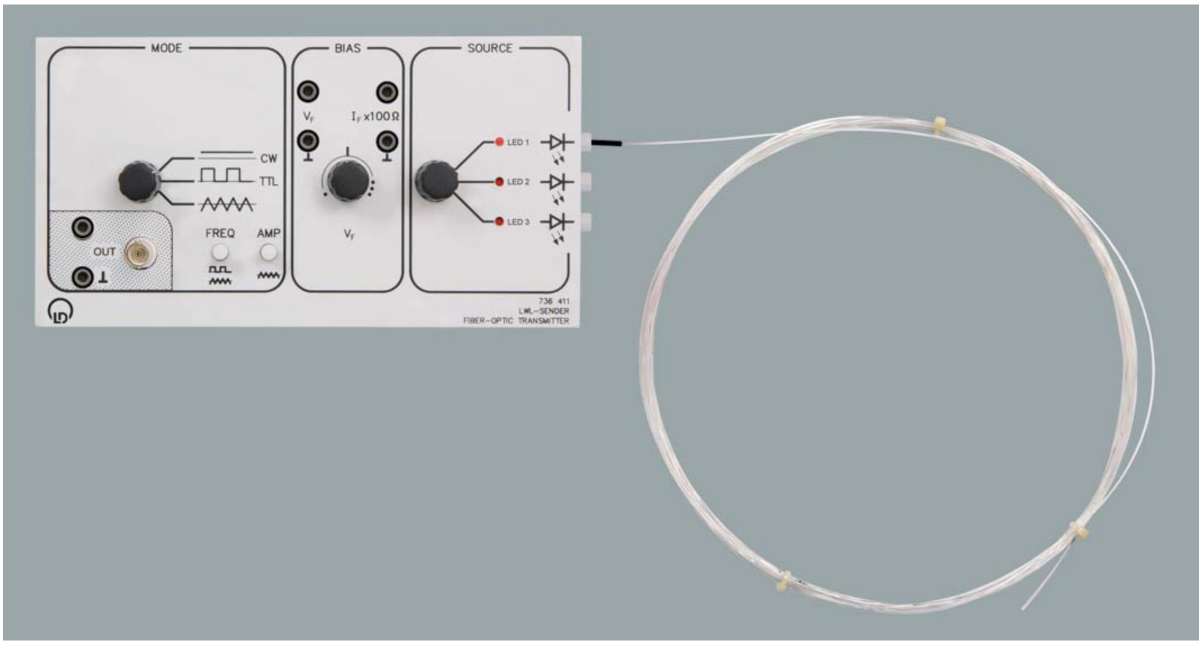
Theory

Large-core-fibers are optical waveguides with a large cross-section Φ in comparison to the wavelength λ. The PMMA fibers used in this training system with a core/clad diameter of 970/1000 µm are among these large-core fiber waveguides. In these kinds of fibers the guiding of light can be explained in terms of beam optics using the principle of total reflection. Only core-modes are guided over long disturbances. These are excited by light, which incidents on the front surfaces of the optical fiber below a particular maximum angle (acceptance angle).

Material

1	736 411	Fiber optic transmitter
1	524 0512	Optical power sensor S
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12 VAC
1	524 013S	Sensor-CASSY 2 Starter
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Guidance of optical fibers: Fiber optic transmitter with fiber, free end in front of white screen (sheet of paper)

Guidance properties of optical fibers

Presetting

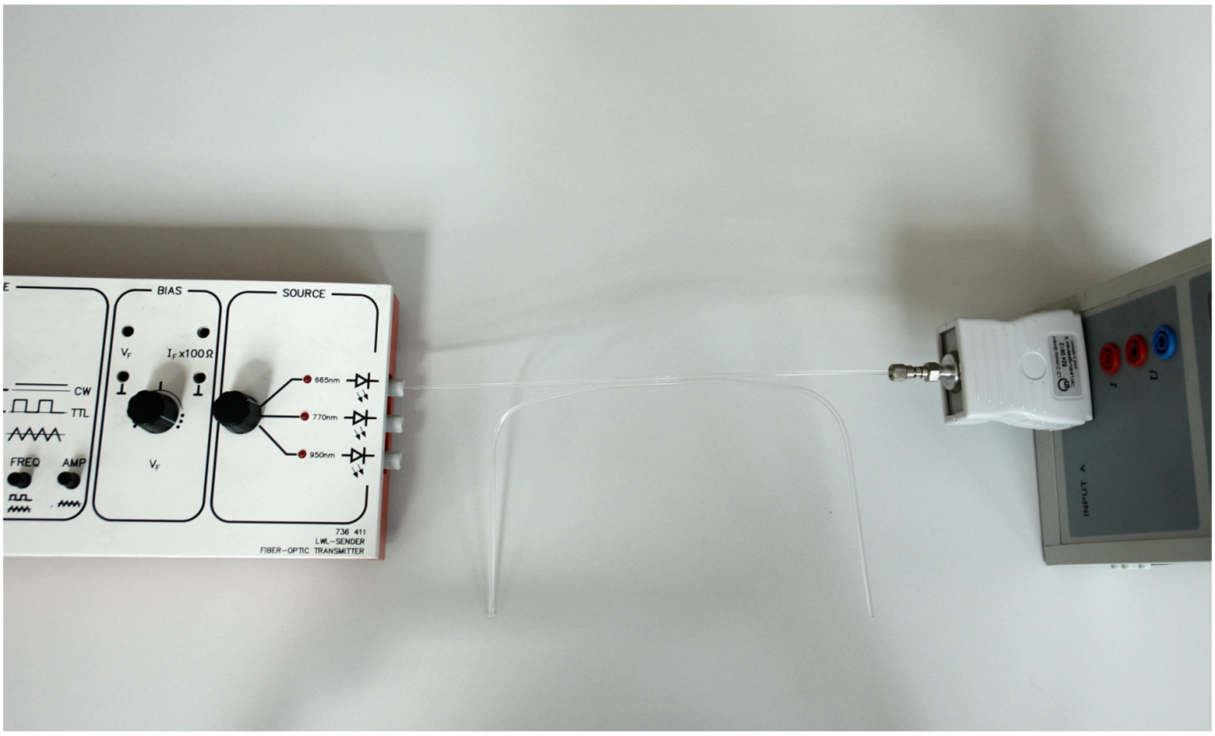
Fiber optic transmitter		Fiber		
MODE	CW			---
BIAS	V_F → right	20 m		---
SOURCE	LED 1	transparent		

Note

The experiment results are best when performed in slightly dimmed conditions.

- Put the transparent fiber into the receptacle of the LED 1.
- Hold the emitting end of the fiber flat on a white piece of paper. Observe how the light exits. What happens when you slightly bend the roll of fiber?
- Make several sharp kinks about 2 cm from the end of the fiber. What do you observe? Scratch the surface open at a few places of the bent piece of fiber. What do you observe?

Total reflection



Total reflection: Fiber optic transmitter, acrylic glass coupler and optical power sensor

The acrylic glass coupler is used here only as the transfer medium between the fiber optic transmitter and the optical power sensor. The Sensor-CASSY is placed *upside down* for easy connection of the coupler.

Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	TTL			
BIAS	V_F → right	acrylic glass coupler		---
SOURCE	LED 1		CASSY	channel A

- Set up the experiment with Sensor-CASSY and optical power sensor S as shown.
- Load the CASSY Lab example TotalReflexionOPS.labs.
- Measure the optical power (Measurement „undisturbed“).
- Now touch the acrylic coupler with your finger. Measure the optical power (Measurement „disturbed“).
- Repeat the experiment with the transparent optical fiber. For this insert the free end into the optical power sensor and hold it there tight. Try to keep from shaking! Enter your measurements into the table.

Optical power / dBm

Measurement undisturbed	Measurement disturbed

Variants

- Try other LED.

Results

Guidance properties of optical fibers

When the light leaves the transparent fiber, this occurs with a more or less clearly recognizable beam cone. Slight pressure on the fiber leads to an increase of bend attenuation. The rolled up fiber illuminates weakly in the area where small turn radii prevail. Sharp kinks cause severe leakage out of the optical fiber. Then the fiber optic waveguide looses to a great degree its capacity to guide light waves. The fiber cladding is destroyed by excessive scratching or roughing of the surface. The total reflection now occurs at the external surface bordering on the air and can easily be distorted. This also becomes visible by a weak illumination of the fiber.

Total reflection

Optical power / dBm

Measurement undisturbed	Measurement disturbed

Acrylic glass does not have any core jacket structure. It guides light waves through total reflection at the glass-air boundary. According to the Goos-Hänchen theory, during total reflection the light waves penetrate several wavelengths deep into the medium with the lower refractive index and then run along the border as surface waves before they return into the medium with the higher refractive index again. These surface waves can easily be disturbed by touching, which leads to a drop in optical power being transmitted along the acrylic glass link. In contrast to simple acrylic glass, the transparent optic fiber has a core jacket structure. The total reflection necessary for light transport occurs here at a boundary protected from external contact. Consequently the optical fiber cannot be disturbed.

Attenuation

Theory

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 the measurement is performed according to the cutback method. Here the optical power P_2 is measured at one end of a known cable length *l*. 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 measurement method is 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 experiments. Thus for the purpose of experimentation the attenuation measurements are described as throughput measurements on premade optical fibers of different length. A typical parameter for an optical waveguide is the attenuation coefficient *a,* which is defined as attenuation per km of waveguide material. The attenuation of an optic waveguide for a fixed wavelength is given by:

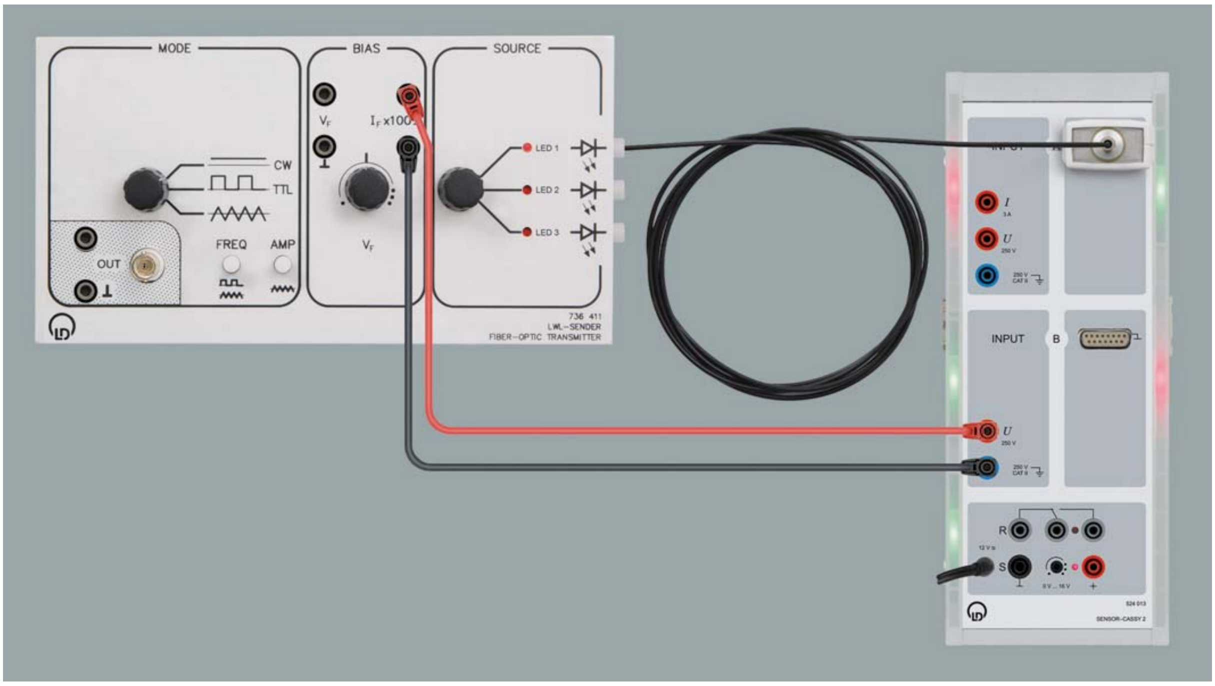
$$\frac{a}{dBkm^{-1}} = \frac{10.000}{\Delta l} \log \frac{P_1}{P_2}$$

Enter Δl in m.

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

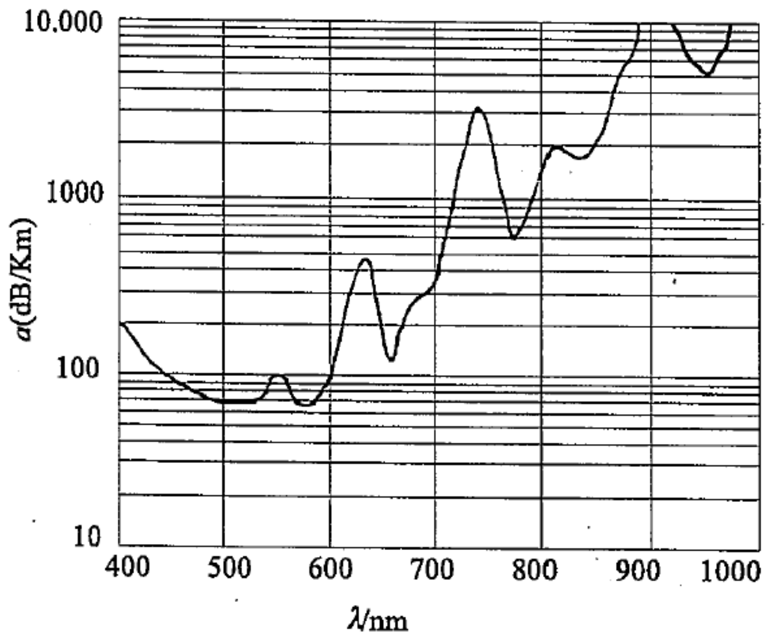
Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	all		
BIAS	V_F → right	lengths	CASSY	Input A
SOURCE	LED 1/2/3			

- Set up the shown experiment
- Select LED 1 with SOURCE.
- Put the fiber with l = 5 m firmly into the connector of the LED.
- Load the CASSY Lab example Attenuation.labs.
- Right mouse click into the instrument PA1 activate *settings sensor input* → 0 ←. The display changes to 0 dB.
- Measure successively the fibers with l = 10/20/50 m.
- Calculate the attenuation a/dBkm^{-1}. For that, insert the attenuation values into the appropriate formulas.
- Repeat the measurement for LED 2 and LED 3 respectively. If necessary, change the settings in CASSY Lab.

		PA1/dB				
I_F/mA	**SOURCE**	**l = 5 m**	**l = 10 m**	**l = 20 m**	**l = 50 m**	**a/dBkm^{-1}**
42.45	LED 1					$a = \frac{1000}{45} a_{50} =$
	LED 2					$a = \frac{1000}{15} a_{20} =$
	LED 3					$a = \frac{1000}{5} a_{10} =$

Variant

- Demonstrate the bend attenuation.



Principal characteristic of attenuation for PMMA

Results

		PA1/dB				
I_F/mA	**SOURCE**	**l = 5 m**	**l = 10 m**	**l = 20 m**	**l = 50 m**	**a/dBkm^{-1}**
42.45	LED 1					$a = \frac{1000}{45} a_{50} =$
	LED 2					$a = \frac{1000}{15} a_{20} =$
	LED 3					$a = \frac{1000}{5} a_{10} =$

Summary

Mean fiber attenuation for die LED 3 is hard to estimate: $a > 3000$ dBkm^{-1}

Interpretation

Of the two attenuation minima between 500 nm and 700 nm the one at $\lambda = 650$ nm is most suitable for link lengths up to 100 m. Furthermore, the switching times for the red LED are shorter than for the possible green emitter at $\lambda = 560$ nm. Consequently LEDs in the visible red range ($\lambda = 665$ nm) are particularly suitable for data transmissions using PMMA. For short link lengths in the range of several meters favorable power /cost ratios can be achieved using very powerful IR-emitters, in spite of the enormous fiber attenuations. If the fiber is bent too severely, then modes are guided flatly through the cladding and out of the waveguide. In this case leaky modes are exited. The propagation in the fiber optic core is also hindered by scattering and absorption. The former can occur at faulty sites (e.g. imperfections or trapped crystals) or at areas with fluctuating dielectric constants. The latter is called Rayleigh scattering. Another important cause for power losses results when light causes molecules to oscillate and is thus converted into thermal energy. Consequently, only those wavelength ranges are used for signal transmission, in which minima arise in the attenuation characteristic curve. Such ranges are called optical windows.

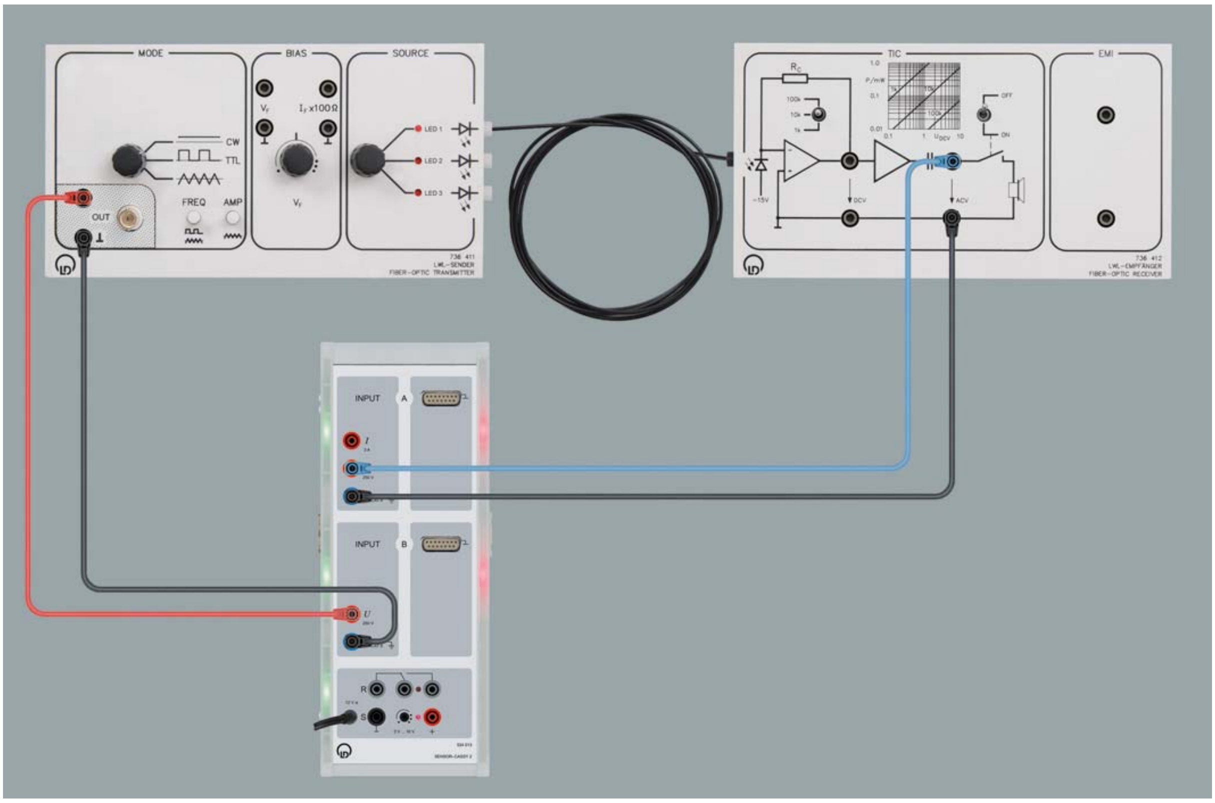
Signal transmission with optical fibers

Material

1	736 411	Fiber optic transmitter
1	736 412	Fiber optic receiver
1	736 421	Set of fiber-optic waveguides and accessories
2	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
2	500 644	Safety connection lead 100 cm, black
1	500 642	Safety connection lead 100 cm, blue
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Analog modulation

Carrying out the experiment



Fiber optic transmitter: Use the OUT-sockets

Fiber optic receiver: Use the AC V-output

Presetting analog modulation

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	Triangle		R_C	10 k
FREQ	→ min	10 m	Output	ACV
AMP	→ max		loudspeaker	ON
BIAS	V_F → variable			
SOURCE	LED 1			

- Set up the shown experiment
- Load the CASSY Lab example Analog.labs.
- Start the measurement by pressing *F9.*
- Enhance the bias voltage of the LED. For it turn the potentiometer V_F slowly to the right.
- Observe the modulating signal V_{OUT} and the received signal V_{ACV} for different bias voltages: BIAS: min. / middle / max.
- Select a frequency for maximum sensitivity of the loudspeaker.
- Sketch the oscillogram with the modulating signal of the signal generator and the demodulated signal at the output of the receiver V_{ACV}.
- Discuss the situation for analog modulation.

Setting the operation point for analog modulation

- Display the current I_F and the voltage V_F at the LED (fiber optic transmitter) for optimum operation point. An optical transmission system consists of which components?

Fiber optic transmitter	
MODE	triangle
FREQ	→ min
AMP	30%, mean, 60° max
BIAS	V_F → variable
SOURCE	LED 1

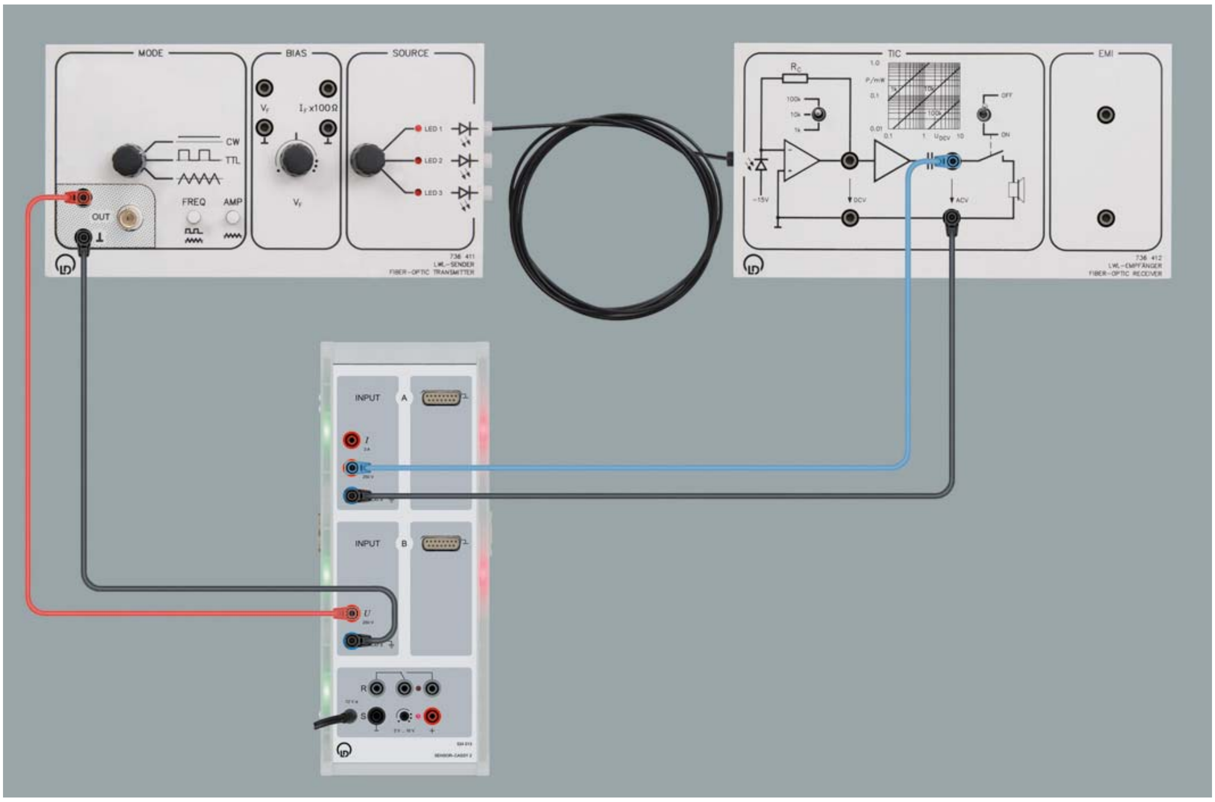
Note: The reduction of the amplitude: AMP < 30% gives parasitic effects.

- Load the CASSY Lab example AnalogCurrent.labs.
- Start the measurement by pressing *F9.*
- Enhance the bias voltage of the LED. For this turn the potentiometer V_F slowly to the right.

Variants

- Change the frequency of the modulating signal.
- Use another LED.
- Switch the loudspeaker on / off.
- Bend the fiber carefully and observe the attenuation.

Digital modulation



Presetting digital modulation

Fiber optic transmitter		Fiber	Fiber optic receiver	
MODE	TTL		R_C	10 k
FREQ	min / max / random	10 m	Output	ACV
SOURCE	LED 1		loudspeaker	ON

- Carrying out the experiment as for analog modulation.
- Load the CASSY Lab example DigitalCurrent.labs.
- Start the measurement by pressing *F9.*
- Sketch the oscillograms of the modulating signal (fiber optic transmitter: OUT) as well as the output voltage U_{ACV} at the fiber optic receiver. Briefly describe the oscillograms!
- Distinguish the signal parameters for analog and digital transmission.

Results

Analog modulation

Bias minimum
Black: modulating signal at OUT
Red: demodulated signal at ACV

Bias middle
Black: modulating signal at OUT
Red: demodulated signal at ACV

Bias maximum
Black: modulating signal at OUT
Red: demodulated signal at ACV

Fiber optic transmitter: current (red) and voltage (black) at the LED, AMP = 30% (ca.)

Fiber optic transmitter: current (red) and voltage (black) at the LED, AMP = mean (ca.)

Fiber optic transmitter: current (red) and voltage (black) at the LED, AMP = 60% (ca.)

Digital modulation

Black: modulating signal
Red: demodulated signal at ACV

Summary

Analog modulation

Analog fiber optic technology is primarily used in instrumentation, open- and closed-loop control technology, where particularly high demands are made regarding the linearity of the transmission channel. The linearity is mainly influenced by the current-power characteristic of the LED. Non-linear properties of the emitter diodes lead to signal distortion. The phase shift between input and output signal amounts to $\phi = 0°$. The wanted signal shows no recognizable non-linear distortion. Consequently, the Total harmonic distortion (THD) factor is small. An amplitude attenuation appears here as a form of linear distortion. This can be corrected using a suitable amplifier (here by selecting R_c). The distortions in the output signal at the fiber optic receiver are dependent on the distortions of the diode current of the LED.

An optical transmission link consists of five components:

- Modulator (control electronics of the LED)
- Electro optical transducer (LED)
- Optical fiber (PMMA)
- Opto-electrical transducer (PIN-photodiode)
- Demodulator (electronics, e.g. transimpedance amplifier)

The forward current I_F cannot be negative ($I_F > 0$). In the range of small diode currents the characteristic changes its differential resistance. For current modulation of the LED, this leads to distortions.

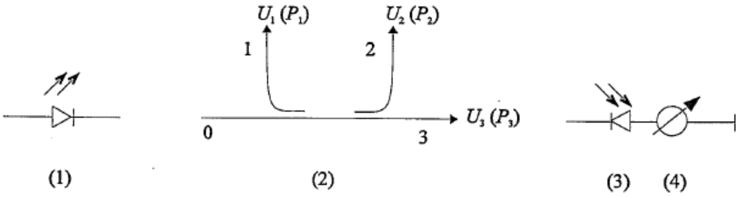
Digital modulation

The modulating digital signal does not require any operating point calibration. In digital transmission links receivers with threshold value decision are used. As long as the threshold value is exceeded by the signal coming from the photodiode, a disturbance free data transmission is possible. Analog signals are described by the frequency, amplitude as well as their curve shapes. In contrast, digital signals in TTL format are always rectangular. They have a fixed level and are defined by their bit frequency, i.e. their transmission capacity. When transmitting digital signals, it must be guaranteed that the transmitted signal can be reproduced in the receiver with sufficient accuracy. To do this, a minimum optical power (minimum number of photons) is required at the receiver, which ensures that a transmitted light pulse - one bit - is recognized.

Fiber coupler

Theory

In the previous experiments transmission links were considered to be point-to-point connections between two terminal devices. Using optical couplers it is possible to use a fiber jointly by several transmitters and receivers. For example in an optical LAN, multiplex signals from different terminals are transmitted via one optical fiber. On the transmitter side the signals from several sources are combined by a multi-port coupler and fed to an outgoing optical fiber. On the receiver side a wavelength selective coupler performs the distribution of the signals to the appropriate receiver. The coupler used in this training system consists of two uncoated dielectric lines, which have direct contact with each other along a length of approx. 45 mm. The lack of optical cladding in this coupler leads to considerable susceptibility to disturbance caused by total reflection. For that reason in real couplers the area outside the coupling zone has to be surrounded by an optical cladding. The power distribution in a coupler is expressed by the so-called coupling factor *CR*. The CR is a decisive quantity of couplers and thus it is investigated in the subsequent experiments.



Schematic representation: (1) light source (2) coupler (3) photo detector

For the coupling ratio CR_{0-1} between port 0 and port 1 the following holds true:

$$CR_{0-1} = \frac{P_1}{P_1 + P_2 + P_3}$$

Usually the optical power emerging at port 3 is much bigger than P1 and P2. Thus:

$$CR_{0-1} \approx \frac{P_1}{P_3}$$

Or, in logarithmic notation:

$$\frac{CR_{0-1}}{dB} \approx \frac{P_1}{dB} - \frac{P_3}{dB}$$

If we calibrate P_3/dB =, we get the following relationship:

$$\frac{CR_{0-1}}{dB} \approx \frac{P_1}{dB}$$

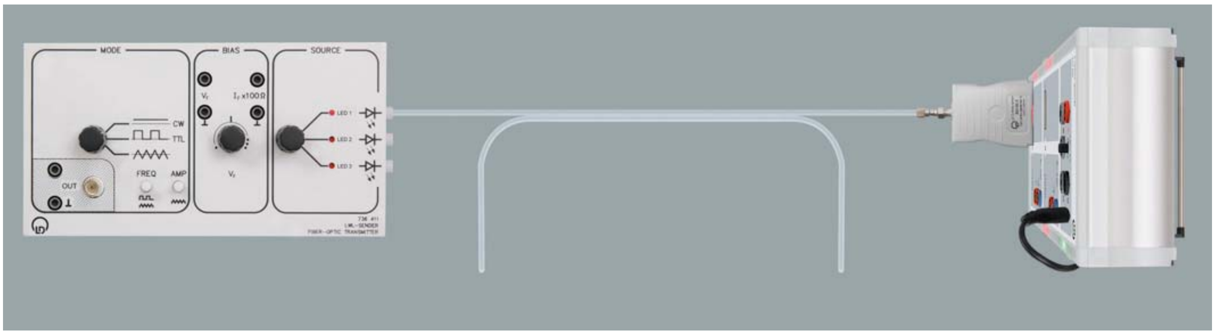
Respectively

$$\frac{CR_{0-2}}{dB} \approx \frac{P_2}{dB}$$

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Sensor-CASSY „upside down“

Presetting of the multiport coupler

Fiber optic transmitter		**Fiber**	**Optical power sensor S**	
MODE	CW			
BIAS	V_F → right	acrylic glass coupler	CASSY	channel A
SOURCE	LED 1 / 2 / 3			

Notes

- The optical coupler is made of acrylic glass. Handle with care and avoid strong bending.
- Before inserting the coupler, the screw nuts of the LED-diode have to be loosened.
- Make sure that the coupler is inserted deeply enough into the receptacles of the LED and the optical power sensor.
- Softly align the fiber optic transmitter, the coupler and the optical power sensor, until the maximum output signal is indicated.
- The ports 0 and 3 can be interchanged. This also inverts the function of the ports 1 and 2.
- It`s common practice to take the absolute value of the coupling ratio (no negative quantities).

Measuring the coupling ratio $CR_{0\text{-}2}$

- Set SOURCE to LED 1.
- Set up the above shown experiment.
- Load the CASSY Lab example CR02.labs.
- Make a right click into the instrument “Optical Power P_{A1}“ to activate *Settings*. Click on: → 0 ←. Reduce V_F, if the display is blinking.
- The display of $CR_{0\text{-}2}$ changes to 0.0 dB.
- Connect the optical power sensor to port 2 of the coupler.
- The display of the meter changes to the actual coupling ratio $CR_{0\text{-}2}$. List the value $CR_{0\text{-}2}$ in the table.
- Subsequently set the SOURCE to LED 2 and LED 3 respectively.
- Repeat the experiment.

Measuring the coupling ratio $CR_{0\text{-}1}$

- Set SOURCE to LED 1.
- Set up the above shown experiment.
- Load the CASSY Lab example CR01.labs.
- Make a right click into the instrument “Optical Power P_{A1}“ to activate *Settings*. Click on: → 0 ←. Reduce V_F, if the display is blinking.
- The display of $CR_{0\text{-}1}$ changes to 0.0 dB.
- Connect the optical power sensor to port 1 of the coupler.
- The display of the meter changes to the actual coupling ratio $CR_{0\text{-}1}$. List the value $CR_{0\text{-}1}$ in the table.
- Subsequently set the SOURCE to LED 2 and LED 3 respectively.
- Repeat the experiment.

SOURCE	$CR_{0\text{-}1}$/dB	$CR_{0\text{-}2}$/dB
LED 1		
LED 2		
LED 3		

Results

Principle of the multimode fiber coupler

SOURCE	CR_{0-1}/dB	CR_{0-2}/dB
LED 1		
LED 2		
LED 3		

Interpretation

- Deviations due to material fluctuations of the coupler are possible. Common values are:

  CR_{0-1}: 18…22 dB

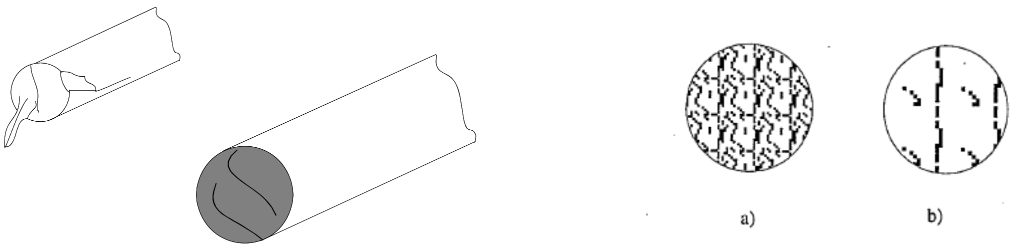
  CR_{0-2}: 6...9 dB

- The coupling ratio in forward direction CR_{0-2} is much bigger than the coupling ration CR_{0-1} in reverse direction. Thus the coupler can be used as directional coupler.

Preparation of fiber ends

Theory

If optical fibers have to be coupled to each other in a network via connectors, high demands are made on the integrity and cleanliness of the ends. Contaminated or even damaged fiber ends generally lead to increased coupling losses. In glass fibers damaged fiber ends frequently have fractures on the edges of the fibers or protruding whiskers. One often sees scratches or pits along the length of greater or lesser severity on PMMA optical fibers. The figure shows the corresponding faults.



Fiber ends: a) unpolished b) polished

In order to achieve smooth, flat and flush fiber ends running at right-angles along the axis, two methods are used in practice for glass fibers:

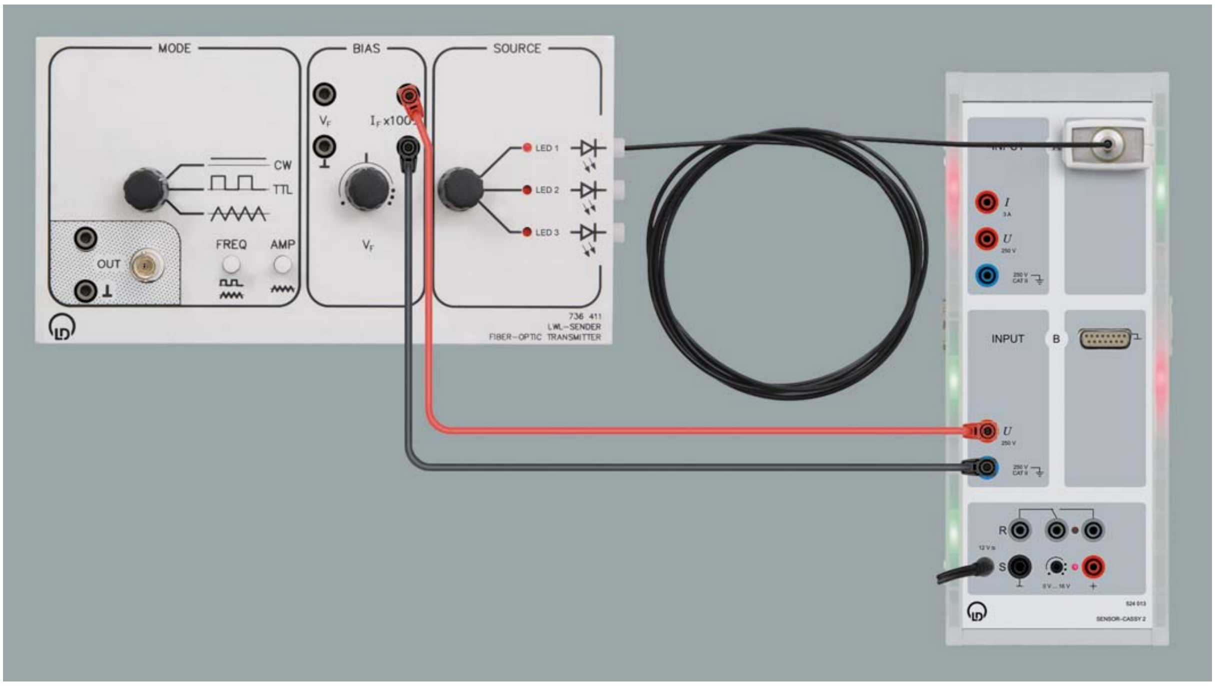
- notching and (defined) breaking off
- grinding and polishing

For the PMMA fibers only the grinding and polishing methods come into question.

Material

1	736 411	Fiber optic transmitter
1	736 421	Set of fiber-optic waveguides and accessories
1	736 429	Fiber-optic microscope
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

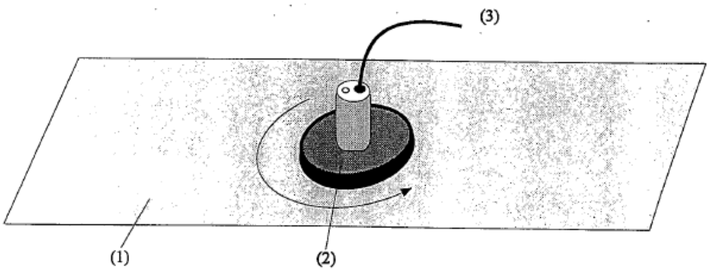
Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	all		
BIAS	V_F → right	lengths	CASSY	channel A
SOURCE	LED 1			

- Set up the shown experiment. Use the fiber optic transmitter, the fiber and the optical power sensor S.
- Scratch the ends of the PMMA-fiber slightly with the abrasive paper.
- Control the result with the fiber-optic microscope.
- Load the CASSY Lab example Coupler.labs.
- Right click into the instrument P_{A1}. Activate *Settings sensor input* → 0 ←. The display changes to 0 dB.
- Start the measurement by pressing *F9*.
- Use the smooth rear side of the abrasive paper for polishing. Use a strip of scotch tape to fasten an approx. 150 mm long segment of the abrasive paper onto a smooth surface (e.g. bench top). Be careful: The surface of the bench should not be susceptible to scratches.



1: Abrasive paper
2: Polishing tool
3: Fiber

- Insert one fiber end into the appropriate hole of the polishing tool. Apply the tool to the abrasive paper and make circular polishing motions. After the polishing procedure, clean the fiber ends with a soft towel or something similar. Reinsert the optical fiber into the experiment and carry out the power measurement again. Enter the measurement results into the table. Determine the gain *g* obtained by polishing.

l/m	**g/dB**
5	
10	
20	
50	

Notes

- The fiber optic microscope (736 429) can be used to check the quality of the fiber ends. Use the loose fiber optic adapter for PMMA optical fibers (ϕ = 2,2 mm contained in the scope of delivery). The internal illumination of the microscope is switched on automatically by unfolding. Fold up again after each use of the microscope, otherwise you will use up the battery. In order to focus correctly, the optical fiber should be pushed in approximately to the interior edge of the adapter. Focusing is performed by turning the knurled wheel.

- The polishing tool has one drilled hole to accommodate the PMMA optical fiber with buffer (ϕ = 2.2 mm) and one drilled hole for PMMA optical fibers without buffer (ϕ = 1 mm). The latter hole can be used to polish the transparent optical fibers.

Results

Preparation of fiber ends

l/m	g/dB
5	
10	
20	
50	

Interpretation

The polishing of one fiber end (PMMA) results in a power gain of 25% (+1.0 dB) approximately.

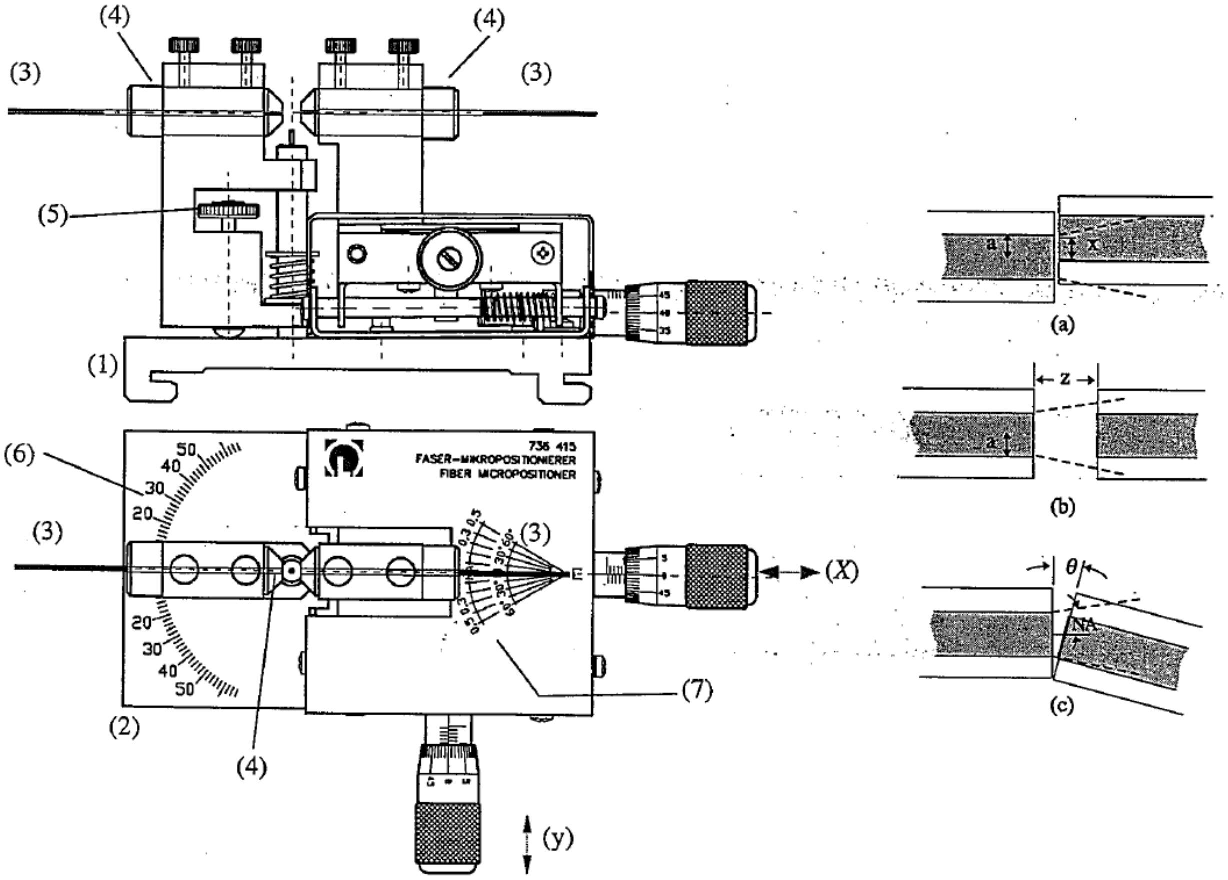
Coupling losses

Theory

Plug connections can contribute additional coupling losses in an optical transmission network due to the following fault sources:

- transversal offset
- longitudinal offset
- angular offset (axes of the optical fibers are at an angle to each other)

Optimally both fiber end faces should be lined up evenly and without any air gaps when two optical fibers are connected to each other.



a: transversal offset
b: longitudinal offset
c: angular offset

Material

1	736 411	Fiber optic transmitter
1	736 415	Fiber micropositioner
1	736 421	Set of fiber-optic waveguides and accessories
1	736 429	Fiber-optic microscope
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
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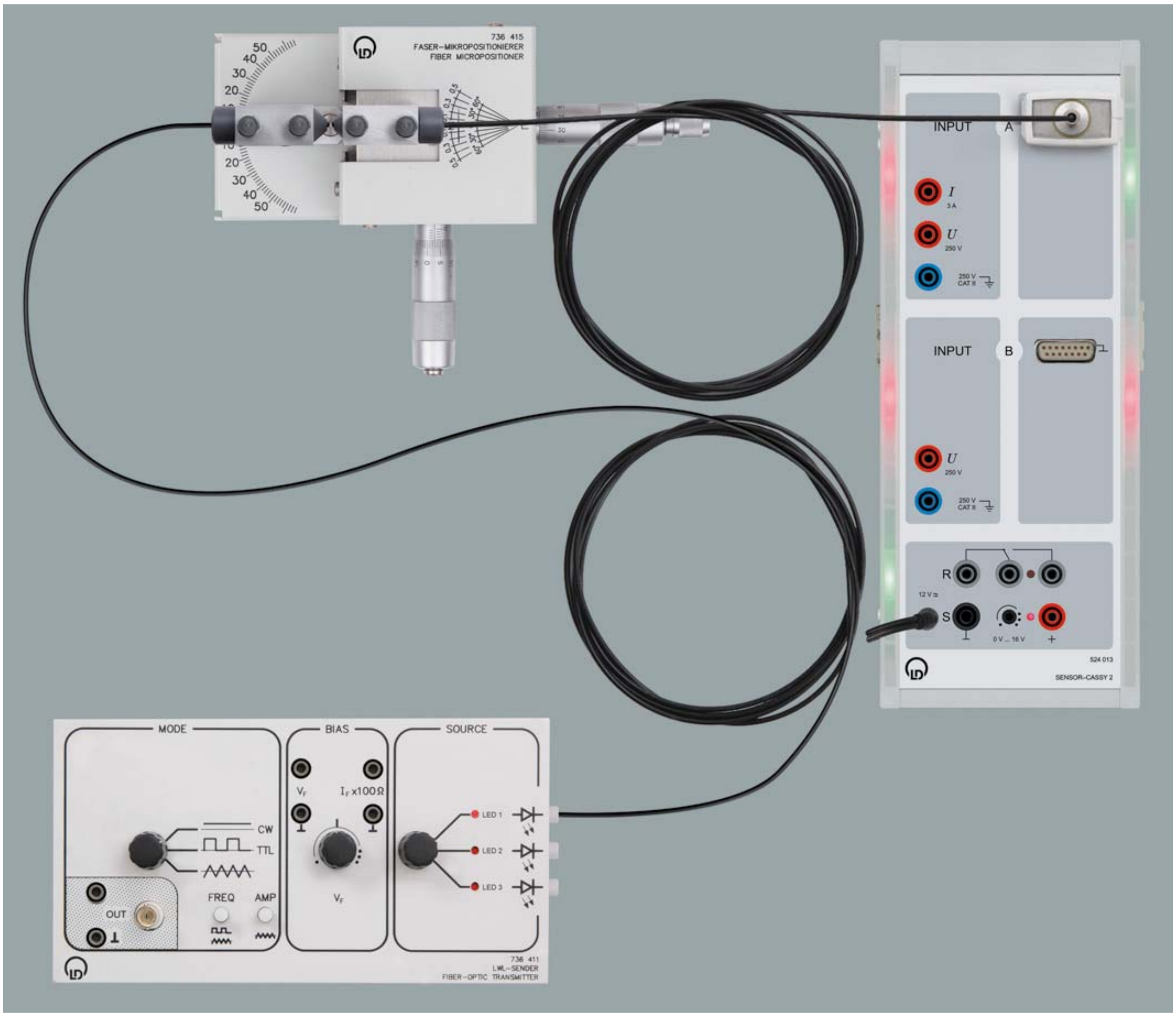
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	fibers		
BIAS	V_F → right	from	CASSY	channel A
SOURCE	LED 1	micropositioner		

Longitudinal offset

- Set the X-micrometer of the fiber-micropositioner to X = 0.00 mm.
- Use the fiber mounts for bare PMMA fibers.
- Use the PMMA sections contained within the micropositioner's scope of supply. Use one section for connection of the LED 1 to the micropositioner and the second cable for the connection between the micropositioner and the optical power sensor.
- Secure the fiber by tightening the thumb screws.
- Load the CASSY Lab example Longitudinal.labs.
- Use the Y-micrometer, the Z-height adjustment and the angular positioner to adjust the fiber ends until you obtain the maximum power. The fiber ends should now be in perfect alignment to each other and there should be practically no air gap between them. Right click into the instrument P_{A1}. Activate *Settings sensor input* → 0 ←. The display changes to 0 dB. Start the measurement by pressing *F9*.
- Now adjust the X-micrometer in steps of 100 µm press each time *F9* again.

Transversal offset

- Set the X-micrometer of the fiber-micropositioner to X = 0.00 mm. (Starting position for the longitudinal measurement).
- Load the CASSY Lab example Transversal.labs. With the instrument PA1 blinking, reduce the diode current of the LED with the potentiometer V_F, until the display gets stationary.
- Make a right click into the Instrument P_{A1}. Activate *Settings sensor input* → 0 ←. The display changes to 0 dB.
- Set the Y-micrometer of the fiber-micropositioner to Y = 0.00 mm (or to the stop position, depending on the type).
- Start the measurement by pressing *F9*.
- Now adjust the Y-micrometer in steps of 100 µm until you reach Y = 6.00 mm and press each time *F9*.
- Set the X-micrometer of the fiber-micropositioner to X = 2.00 mm.
- Repeat the measurements.

Variant

- Repeat the experiment for LED 2 and LED 3.

Results

Losses by longitudinal offset
Black: linear representation
Red: logarithmic representation

Transversal coupling losses X = 0.00 mm
3dB-width: 1100 µm
Black: linear representation
Red: logarithmic representation

Transversal coupling losses X = 2.00 mm
3dB-width: 2000 µm
Black: linear representation
Red: logarithmic representation

Summary

Longitudinal offset

PMMA demonstrates a field distribution at the air gap which can be approximated by a falling exponential function. In PMMA cables an air gap of X = 1500 µm generates an attenuation of approx. 3 dB, i.e. already half the optical power is lost. There is no detectable difference between the air-gap attenuation for LED 2 and LED 3.

Transversal offset

The transversal field distribution in front of a multimode fiber shows a dependency which can be approximated with a Gaussian error curve. The Gaussian bell curve is given by:

$$E = e^{-cY^2}$$

Here the factor *c* depends on the longitudinal offset *X* of the two fiber ends. With increasing distance *X* the maxims become flatter and broader.

Reduction of reflexion losses

At every boundary which separates areas with different refractive indices – a part of the incident light is reflected. For the shown case, theory gives the following reflection factor:

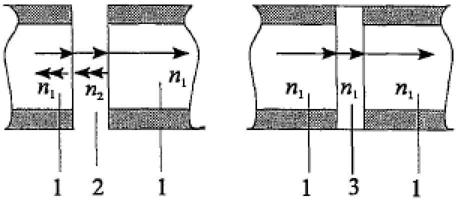
$$r = \frac{n_1 - n_2}{n_1 + n_2}$$

The equation corresponds to the reflection factor on lines. The power P_r reflected at a fiber end is proportional to the square of the reflection factor:

$$P_r = r^2 P_i$$

If for the core glass of the optical fiber we take n_1 = 1,5 and for n_2 the refractive index for air (n_2 = 1) then we obtain:

$r = 0.2$ $r^2 = 4\%$



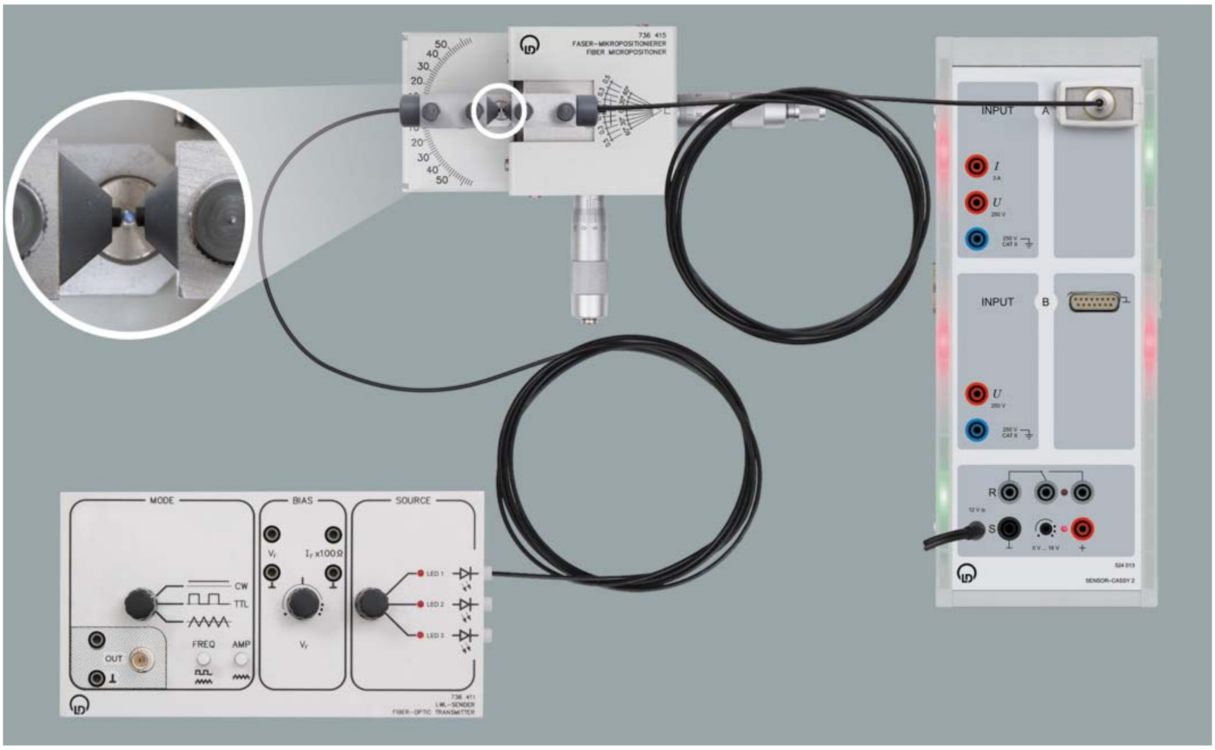
For perpendicularly exiting light approx. 4% of the incident optical power P_i is reflected at every glass-air boundary. For an air-gap plug with 2 glass-air end surfaces this means a reduction in effective power amounting to 8%. This power loss can be avoided by filling the space between the fiber end surfaces with an index paste or an immersion oil. In both cases the space between is adapted to the refractive index of the core glass. Immersion oil is not very practical because it flows out of the air gap. Index pastes attract dirt, collecting dust and other particles. When handled without care the particles trapped in the index paste can scratch the fiber end surfaces (abrasion). In this experiment water is used for index matching, because of its unlimited availability. The refraction index of water is about n_2 = 1.33.

Material

1	736 411	Fiber optic transmitter
1	736 415	Fiber micropositioner
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	564 482	Book: Experiments with PMMA fibers
1		PC
		A drop of water

Note: The fiber end surfaces of optical fibers have to be polished for this experiment. If you experiment with unpolished fibers the transmitted power increases up to 100% when the air gap is moistened. Index adaptation only contributes approx. 8...10% to this result, whereas the main improvement is produced by the optical improvement of the end surfaces!

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW	fibers		
BIAS	V_F → right	from	CASSY	channel A
SOURCE	LED 1	micropositioner		

- Assemble the experiment as shown. Take the two optical fibers with length 1 m from the accessory of the micropositioner (with polished surfaces, see note above).
- Use the mounts for bare PMMA fibers in the fiber micropositioner.
- Set the X-micrometer of the fiber-micropositioner to X = 0.00 mm.
- Insert the two optical fibers into the mounts, until the fiber ends get into contact.
- Separate the two fiber ends by setting the X-micrometer of the fiber-micropositioner to X = 0.50 mm
- Load the CASSY Lab example ReflexionLoss.labs.
- Use the Y-micrometer, the Z-height adjustment and the angular positioner to adjust the fiber ends until you obtain the maximum power. The fiber ends should now be in perfect alignment to each other with an air gap X = 0.50 mm between them.

- Make a right click into the instrument “Optical Power P_{A1}” to activate *Settings.* Click on: → 0 ←. Reduce V_F if the display is blinking.
- The displays on the attenuation instruments G and g change to 100 % respectively to 0.0 dB.
- Apply a drop of water between the fiber-ends. See enlarged part of experiment set up.
- Record the linear and logarithmic attenuation G and g in the table.
- Dry the air gap between the fiber ends.
- Repeat the experiment for LED 2 and LED 3.
- Give an interpretation

Reduction of the reflection losses

SOURCE	**G/%**	**g**
LED 1		
LED 2		
LED 3		

Results

- Index matching results in a power gain due to the bridging of small air gaps. If in the experiment the air gap is made too large, then additional losses arise, which rapidly become even greater on account of the large NA (numerical aperture) of PMMA optical fibers.
- With two glass-air junctions we could expect a linear increase from G = 100% G = 108% (g = +0.33 dB).
- Deviations from that theoretical value are due to the huge air gap (0.5 mm) which provokes a strong spillover of light from the emitting fiber. With increasing distance between the two fibers, an even smaller amount of light can be coupled into the receiving fiber (under dry conditions). Thus the result after index matching is emphasized.
- Each plug connection adds approximately 1 dB losses into the optical power budget. In the case of scratched fiber ends the power gain appears to be greater (effect of coarseness).
- The reduction in reflection losses is relatively constant with the wavelength of the light.

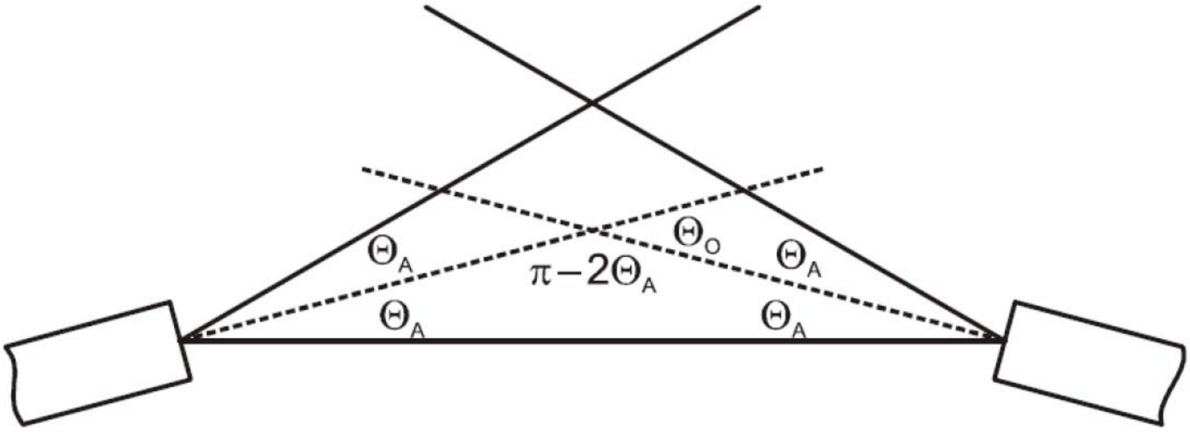
Reduction of the reflexion losses

SOURCE	G/%	g
LED 1		
LED 2		
LED 3		

Numerical aperture

Theory

The numerical aperture (NA) is an important parameter in fiber optics. The greater the NA, the greater the coupling effectiveness, i.e. the more light incident at an angle can be coupled into the fiber. Also the losses resulting from bends decrease with increasing numerical aperture. In the case of short fiber lengths a portion of the light is also propagated in the cladding or in higher modes. Due to the higher attenuation for these modes the numerical aperture declines with increasing fiber length and reaches its constant value only after a certain fiber length.

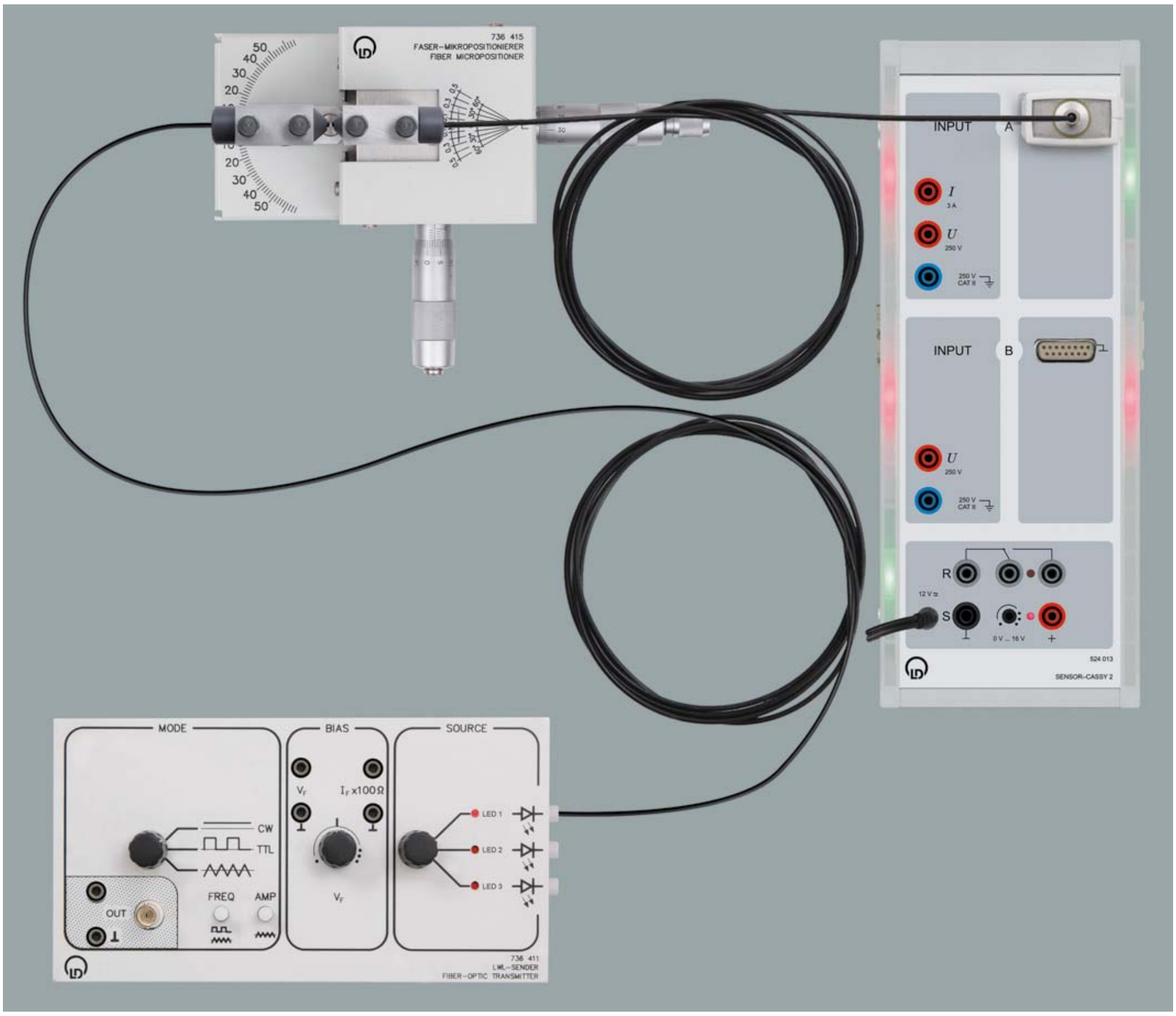


Measurement of the acceptance angle θ_A: The axes of the fibers intercept at the half aperture angle θ_0.

Material

1	736 411	Fiber optic transmitter
1	736 415	Fiber-micropositioner
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	500 644	Safety connection lead 100 cm, black
1	500 641	Safety connection lead 100 cm, red
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		**Fiber**	**Optical power sensor S**	
MODE	CW	Fibers		
BIAS	V_F → right	from	CASSY	channel A
SOURCE	LED 1	micropositioner		

- Set up the shown experiment.
- Load the CASSY Lab example NumAp.labs.
- Start the measurement by pressing *F9.*

- In case the display is blinking, turn the potentiometer V_F back. Right click into the instrument P_{A1}. Activate *settings sensor input* → 0 ←. The display changes to 0 dB.
- The determination of the NA with the aid of the fiber micropositioner 736 415, is based on the measurement of the acceptance angle θ_A. This is half the aperture angle θ_0 of the cone within which light can penetrate into the fiber. The aperture angle θ_0 is directly related to the acceptance angle and the *NA*.

$$\Theta_A = \frac{1}{2}\Theta_0$$

$$NA = \sin\theta_A = \sqrt{(n_1^2 - n_2^2)}$$

- The aperture angle θ_0 can be read off directly from the angular scale of the micropositioner. Use the bare PMMA fiber sections and the corresponding fiber mounts included with the fiber micropositioner.
- Insert the bare ends into the fiber mounts of the micropositioner. The fiber ends should be aligned symmetrically to the axis of rotation. The space between the fiber-ends amounts to approx. 2 mm.
- Align the angular positioner to 0°. Use the Y-manipulator to calibrate to minimum the transversal offset. This gives the maximum optical power. Proceed in the same fashion to calibrate the Z-axis for the height adjustment using the thumb screw.
- Now carefully turn the angular positioner in both directions. Closely observe the receiving signal. Note down the angles θ_{01} and θ_{02} at which the optical power has dropped below –15 dB. Calculate the mean acceptance angle and the NA.

Determination of the NA

SOURCE	θ_{01}/GRD	θ_{02}/GRD	θ_A/GRD	NA
LED 1				
LED 2				
LED 3				

Note

- You can roughly determine the acceptance angle θ_A and the NA from the aperture angle θ_0 of the beam cone by holding the fiber end surfaces to the scale of the micropositioner. Protect the (weak) light cone from the effects of outside light with your hand.

Results

Summary

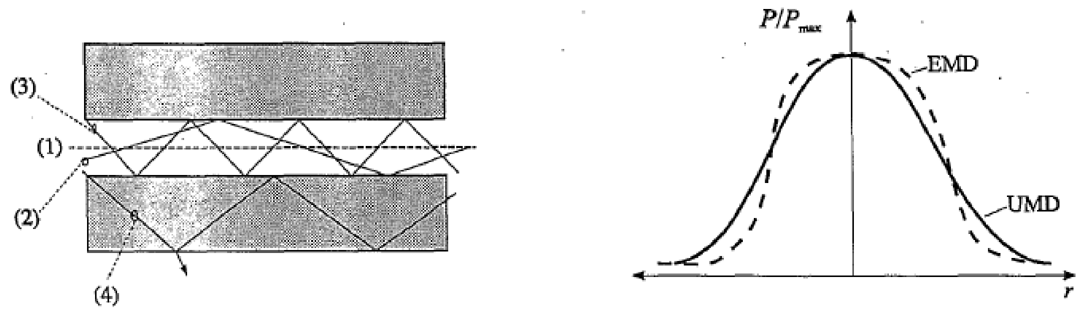
Coupling light into the fiber after falling below the acceptance angle is performed gradually, not abruptly. The reason for this is the beam characteristic of the fiber end. Therefore when determining the acceptance angle θ_A you need a little practice to detect this gradual transition.

Determination of the NA

SOURCE	θ_{01}/GRD	θ_{02}/GRD	θ_A/GRD	NA
LED 1				
LED 2				
LED 3				

Suppression of undesired modes

Theory



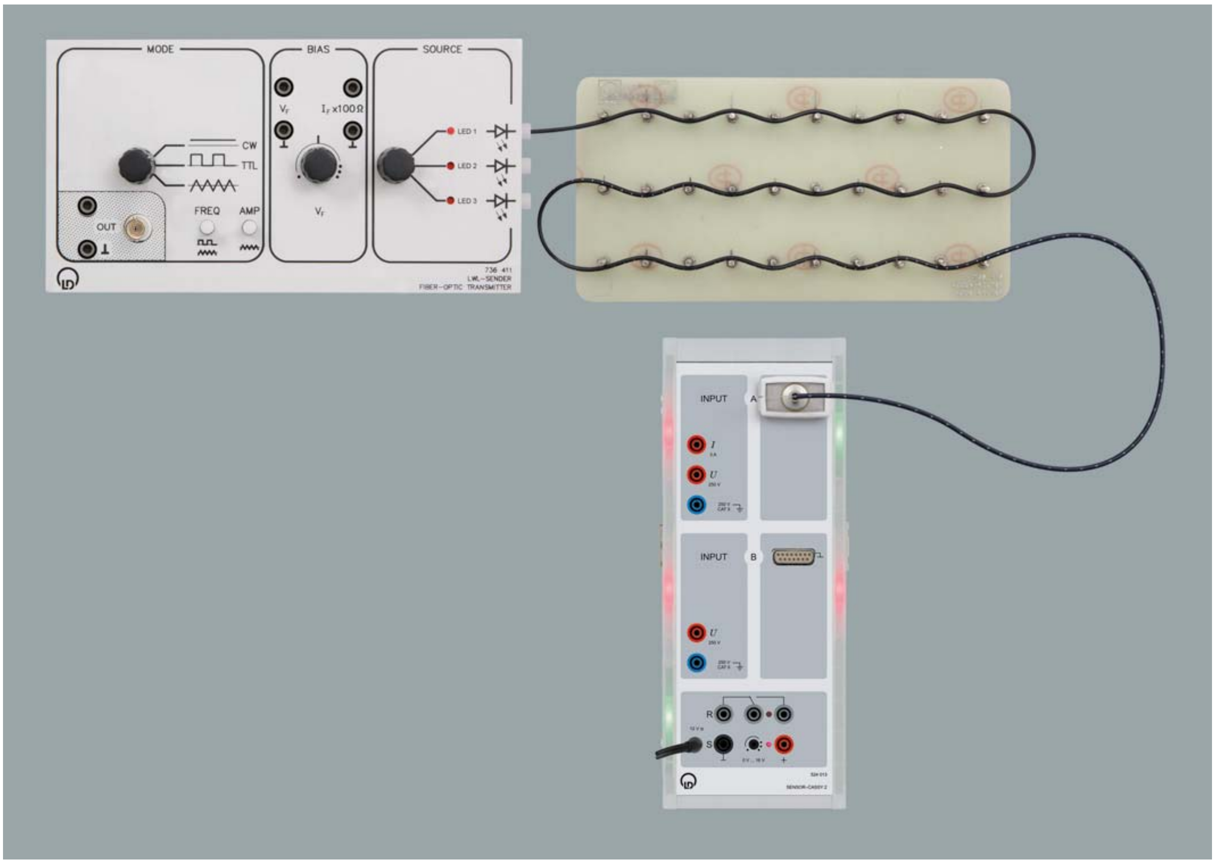
In a step index fiber only light beams can propagate which strike the fiber end at under a certain angle. Incident light at unacceptable angle is cancelled out due to destructive interference caused by repeated reflections along its path through the fiber. Beams propagating at accepted angles are called modes. When a beam is launched at the fiber end, this can result in so-called cladding modes. These beams are sharply reflected around the fiber axis. Although cladding modes are allowed, they propagate - as their name suggests - in the optical cladding of the fiber. Because these normally have a higher attenuation than modes propagating in the core glass the power of the cladding modes rapidly decreases with increasing fiber length. Furthermore cladding modes penetrate into the outer jacket. Under uniform illumination of the fiber end all accepted modes are excited (UMD).

Due to the more severe attenuation of the cladding modes, the uniform distribution decreases with increasing fiber length. The light is propagated more and more in modes of attenuation lower order. The attenuation (a/dBkm^{-1}) reaches a constant value. In the fiber an equilibrium mode distribution settles in (EMD). Cladding modes have to be avoided at high modulation frequencies and short fiber segment lengths due to mode dispersion arising. They also pose a problem when performing attenuation measurements. To achieve mode equilibrium and to suppress disturbing cladding modes so-called mode filters (mode strippers) are used. These increase the losses for higher modes by causing artificially induced bend attenuation. Thus EMD distribution can be produced even on short fiber lengths.

Material

1	736 411	Fiber optic transmitter
1	736 416	Mode filter
1	736 421	Set of fiber-optic waveguides and accessories
1	562 791	Plug-in power supply 12VAC
1	524 013S	Sensor-CASSY 2 Starter
1	524 0512	Optical power sensor S
1	564 482	Book: Experiments with PMMA fibers
1		PC

Carrying out the experiment



Presetting

Fiber optic transmitter		Fiber	Optical power sensor S	
MODE	CW			
BIAS	$V_F \rightarrow$ right	Fiber from micropositioner	CASSY	channel A
SOURCE	LED 1			

- Set up the shown experiment
- Guide the fiber without strong bendings from the LED to the optical power meter.
- Load the CASSY Lab example ModeAtt.labs.
- Make a right click into Instrument P_{A1}. Activate *settings sensor input* → 0 ←. The display changes to 0 dB.
- Start the measurement by pressing *F9.*
- Now lead the fiber across the mode filter. Measure the optical attenuation in function of the number of bendings *n*. Press each time *F9*.
- Display graphically the bending attenuation as a function of bendings *n*.

Number of bendings *n*	a_{log} / dB
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	
21	
22	
23	
24	

Variant

- Repeat the experiment for different fiber lengths and at different wavelengths.

Results

Number of bendings *n*	a_{log} / dB
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
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24	