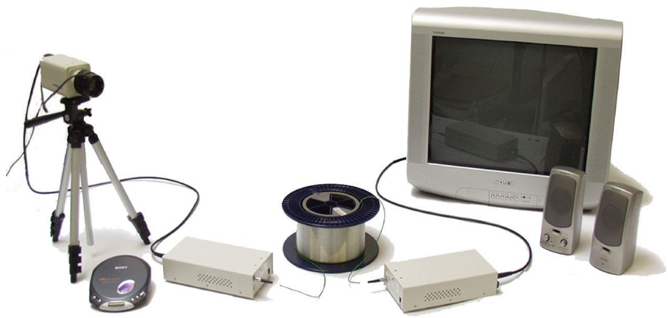
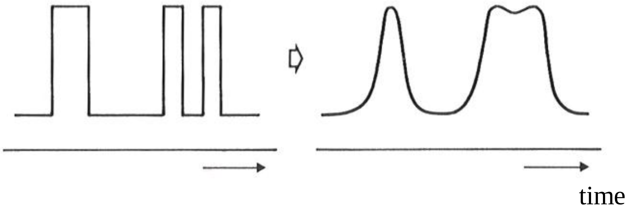
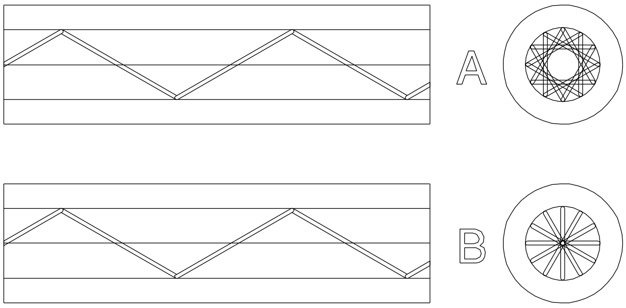
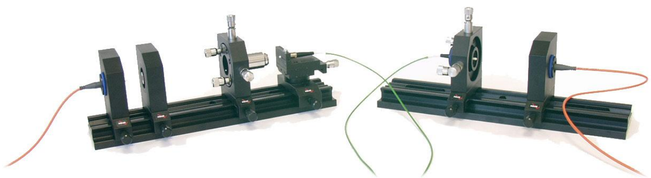
Experiment 25

Data Transmission via Optical Glass Fibre









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1 Introduction

It was in 1866 when the British ocean steamer "Great Eastern" traversed the Atlantic, loaded with a very unusual cargo: 7,000 tons of one single copper wire, vanishing bit by bit in the deep sea – the first transatlantic telegraph line was laid, and the first step to a world wide communication net was done.

Fig. 1: "Great Eastern" on her way to America

Nowadays, after almost 150 years of exciting development the traditional electrical lines become substituted by optical fibres. While by the copper wire 36 phone calls could be transmitted in parallel, an optical fibre line is able to handle several ten thousand calls at the same moment. But not only phone calls are transmitted. All kind of data as well as TV shows rush through the lines today.

Further advantages of a fibre line are its low weight (about one hundredth of the weight of a copper cable), chemical robustness to sea water, insensibility to electrical flashes and induction, and – probably most important – less amplifiers are needed compared to electrical lines. While signals in copper phone lines have to be amplified each 1.5 km, in optical lines the distance of the so called repeaters can be 50 km to 100 km.

The idea of using light in a light conducting material as a transmitter for information reaches back to H. Buchholz ("Die Quasioptik der Ultrakurzwellenleiter", 1939), but only the invention of semiconductor lasers in 1962 opened the way for the realization of his idea. Laser diodes can transform short electrical signals into optical pulses. Their emitted light in the near infrared range matches ideally the window of high transmission of the most glasses. Nevertheless, there are great demands made on the glass itself, especially on its purity. For instance, a seven centimetres thick layer of normal window-glass dims light by a factor of two – completely out of the question for optical data transmission. In an optical fibre light suffers the same reduction of intensity only after a few thousand metres of travelling. This can be achieved only by an enormous reduction of the impurities in the glass. There is not more than one impurity among a billion or more atoms in the glass allowed.

To avoid losses by emerging of the light through the wall of the fibre the light is kept within the core by total reflection. Therefore the core of the fibres has diameters down to µm, only a few wavelengths of the transmitted light, what makes the coupling of the beam to the fibre not easy.

Since the time of the first laser diodes a lot of research activities have been done, developing new semiconductor lasers, modulation techniques of the light, and investigations in suitable fibre materials. But still, this is one of the most important branches of the ongoing development with the main topics: minimization of transmission losses, cheaper and maintenance-free repeaters or even amplification of the signals within the fibre material.

In our experiment the transmission of signals from a CCD camera or a CD player via an optical fibre is demonstrated. For that electrical signals have to be transformed into sequences of optical pulses which can be sent through the fibre. This happens in a transmitter unit, containing a high speed modulator. The modulator drives a laser diode which is able to emit sequences of short light pulses. The optical pulses are picked up by an ST plug and are transmitted by a multimode fibre. The output conjunction of the fibre feeds the light signals in a receiver unit provided with a fast photodiode. The detected pulses are converted to electrical signals and the transmitted information can be displayed by a video monitor or played back by loudspeakers.

In an extended version of the experiment the light signals from the transmitter are not fed in the long transmission fibre directly, but via a light coupling unit. Also the coupling to the receiver is done by means of a second coupling unit. To achieve data transmission a proper alignment of both units has to be performed.

2 Basics

There is hardly any book in optics which does not contain the experiment of Colladan (1861) on total reflection of light. Most of us may have enjoyed it during the basic physics course.

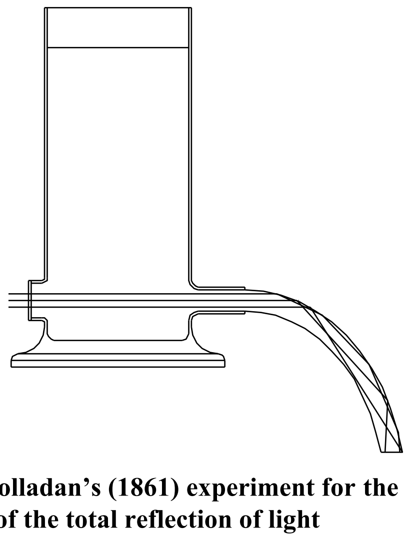

Fig. 2: Colladan's (1861) experiment for the demonstration of the total reflection of light

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An intensive light beam is introduced into the axis of an out flowing water jet. Because of repeated total reflections the light can not leave the jet and it is forced to follow the water jet. It is expected that the jet remains completely darken unless the surface contains small disturbances. This leads to a certain loss of light and it appears illuminated all along its way. Effects of light created in this way are also known as „Fontaines lumineuses". They please generally the onlookers of water games. This historical experiment already shows the physical phenomena which are basic in fibre optics. The difference of this light conductor to modern fibres is the dimension which for a fibre is in the order of magnitude of the wavelength of light. If we designate the diameter of a light guide with d we can state:

„Fontaines lumineuses"	$d >> \lambda$
Multimode fibres	$d > \lambda$
Monomode fibres	$d \approx \lambda$

For the fibres manufactured these days this leads to further effects which can not be described exclusively by total reflection. Their understanding is of special importance for optical communication technology. These effects can be derived by a formalism basing on Maxwell's equations (the interested student can find a comprehensive deduction in Exp. 12, Fibre Optics). For our aim it is not compulsory to know this formalism.

2.1 Fibres as light wave conductors

Glass fibres as wave conductors have a circular cross section. They consist of a core of refractive index n_k. The core is surrounded by a glass cladding of refractive index n_m slightly lower than n_k. Generally the refractive index of the core as well as the refractive index of the cladding is considered homogeneously distributed. The final direction of the beam is defined by the angle Θ_e under which the beam enters the fibre. Unintended but not always avoidable radiation and cladding waves are generated in this way. For reasons of mechanical protection and absorption of the radiation waves the fibre is surrounded by a protective layer.

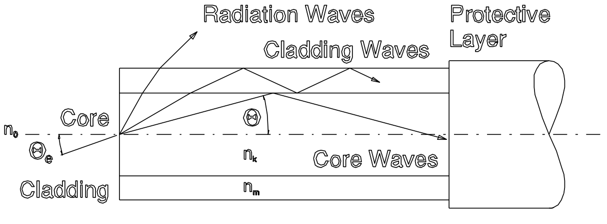

Fig. 3: Step index fibre

Fig. 3 reveals some basic facts which can be seen without having solved Maxwell's equations. Taking off from geometrical considerations we can state that there must be a limiting angle Θ_c for total reflection at the boundary between cladding and core.

$$\cos(\Theta_c) = \frac{n_m}{n_k} \qquad \textbf{(2.1.1)}$$

For the angle of incidence of the fibre we use the law of refraction:

$$\frac{\sin(\Theta_{ec})}{\sin(\Theta_c)} = \frac{n_k}{n_0}$$

and receive:

$$\Theta_{ec} = \arcsin\left(\frac{n_k}{n_0} \cdot \sin\Theta_c\right).$$

Using equation (2.1.1) and with $n_o = 1$ for air we finally get:

$$\Theta_{ec} = \arcsin\left(\sqrt{n_k^2 - n_m^2}\right)$$

The limiting angle Θ_{ec} represents half the opening angle of a cone. All beams entering within this cone will be guided in the core by total reflection. As usual in optics here, too, we can define a numerical aperture A:

$$A = \sin\Theta_{ec} = \sqrt{n_k^2 - n_m^2} \qquad \textbf{(2.1.2)}$$

Depending under which angle the beams enter the cylindrical core through the cone they propagate screw like or helix like. This becomes evident if we project the beam displacements onto the XY-plane of the fibre. The direction along the fibre is considered as the direction of the z-axis. A periodical pattern is recognised. It can be interpreted as standing waves in the XY-plane. In this context the standing waves are called oscillating modes or simply modes. Since these modes are built up in the XY-plane, e.g. perpendicularly to the z-axis, they are also called transversal modes. Modes built up along the z-axis are called longitudinal modes.

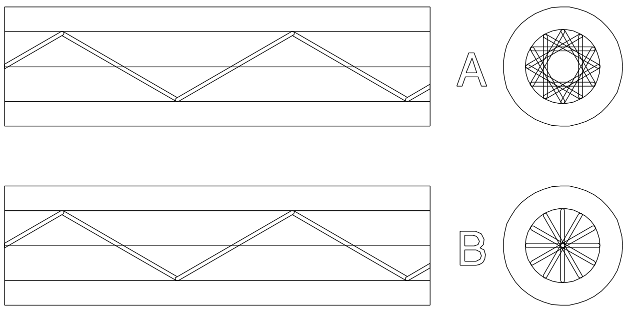

Fig. 4: Helix (A) and Meridional beam (B)

2.2 Types of fibres

Assuming a bunch of light rays entering the fibre, it is obvious that the rays with a bigger angle Θ are more often reflected on the cladding, what causes a longer pathway within the fibre, and finally, they exit the fibre later than rays with small Θ. If light is applied in short pulses this behaviour leads to a temporal smear out of the pulse: the pulse becomes longer (so called mode dispersion). Fig. 5 illustrates that this effect limits the pulse frequency. The maximal possible bandwidth of the transmitted signals is restricted by the fibre, not by the repetition rate of the laser diode. The steep rising and trailing edges of the pulses are smoothened and in the case of short distances of pulses the modulation depth is decreased drastically.

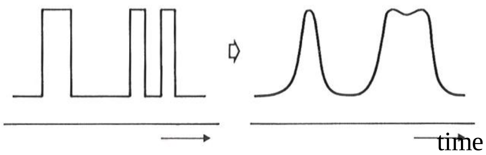

Fig. 5: Mode dispersion in an optical fibre

To increase the bandwidth fibres with graded index profile were developed, i. e. the index continuously rather than stepwise decreases from the axis of the fibre to the cladding. Here the light beam is not reflected but bent back to the centre (Fig. 6). The fibre works like a lens and induces so called self focusing of the beam. Such a fibre is more difficult in manufacturing and therefore more expensive, but the broadening of the pulses can be reduced from about 30-50 ns/km for step index fibres to 0.1-1 ns/km.

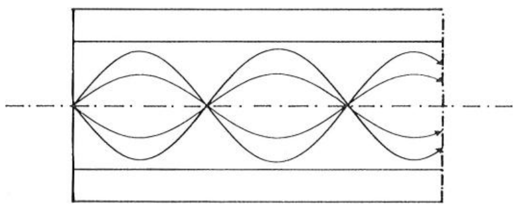

Fig. 6: Modes in a graded index profile fibre

A further step is to allow only one longitudinal mode to travel within the fibre. As a result such single mode fibres have a core with a diameter of only a few nanometres. Now the bandwidth is limited not by the dimensions of the fibre but only by the dispersion of the material. For our experiment, however, with pulses of several nanoseconds the bandwidth of a multimode fibre is sufficient.

For a deeper understanding of the mode generation and their properties it is necessary to solve the Maxwell equations under respect of the fibre boundary conditions.

2.3 Coupling of light

We are facing the problem to couple a beam of light to a fibre, respectively to introduce it into a fibre, the diameter of which is in the order of magnitude of 4-10 µm and in so far comparable to the wavelength of light. To get a sufficient high excitation of the fundamental mode of the fibre, the beam of the light source has to be focused to a diameter of this order of magnitude. Under these circumstances the laws of geometrical optics fail because they anticipate parallel light beams or plane light waves which in reality exist only in approximation.

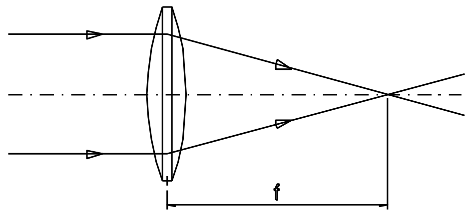

Fig. 7: Focusing two beams in geometrical optics

Real parallel light beams do not exist in reality and plane wave fronts exist only at a particular point. The reason for the failure of geometrical optics is the fact that it has been defined at a time where the wave character of light was still as unknown as the possibility to describe its behaviour by Maxwell's equations.

To describe the propagation of light one has to solve the wave equation. With the condition of spherical waves propagating in z-direction within a small solid angle, the solution of the wave equation provides fields which have a Gaussian intensity distribution over the cross section of the beam. Therefore they are called Gaussian beams. Similar to light in a fibre the Gaussian beams exist in different modes depending on the actual boundary conditions. Such beams, especially the Gaussian fundamental mode (TEM_{00}) are generated with preference by lasers. But the light of any light source can be considered as the superposition of many such Gaussian modes. Still, the intensity of a particular mode is small with respect to the total intensity of the light source.

The situation is different for the laser. Here the total light power can be concentrated in the fundamental mode. This is the most outstanding difference with respect to ordinary light sources next to the monochromasy of laser radiation. Gaussian beams behave differently from geometrical beams.

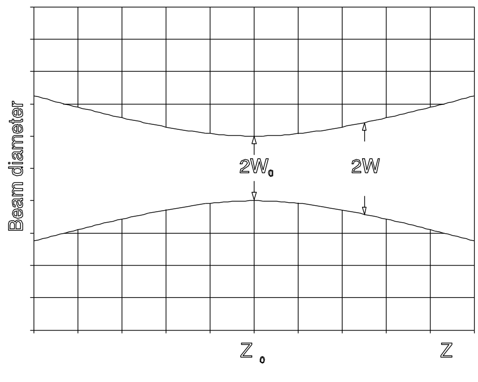

Fig. 8: Beam diameter of a Gaussian beam as fundamental mode TEM_{00} and function of z.

A Gaussian beam always has a waist. The beam radius w results out of the wave equation as follows:

$$w(z) = w_0 \cdot \sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

w_0 is the smallest beam radius at the waist and z_r is the Rayleigh length

$$z_R = w_0^2 \frac{\pi}{\lambda}$$

In Fig. 8 the course of the beam diameter as a function of z is represented. The beam propagates within the direction of z. At the position $z = z_0$ the beam has the smallest radius. The beam radius increases linearly with increasing distance. Since Gaussian beams are spherical waves we can attribute a radius of curvature of the wave field to each point z. The radius of curvature R can be calculated using the following relation:

$$R(z) = z + \frac{z_r^2}{z}$$

This context is reflected by Fig. 9. At $z = z_r$ the radius of curvature has a minimum. Then R increases with 1/z if z tends to $z = 0$. For $z=0$ the radius of curvature is infinite. Here the wave front is plane. Above the Rayleigh length z_r the radius of curvature increases linearly. This is a very essential statement. Due to this statement there exists a parallel beam only in one point of the light wave, to be precise only in its focus. Within the range

$$-z_r \le z \le z_r$$

a beam can be considered as parallel or collimated in good approximation. In Fig. 10 the Rayleigh range has been marked as well as the divergence Θ in the distant field, that means for $z >> z_0$. The graphical representations do not well inform about the extremely small divergence of laser beams another outstanding property of lasers.

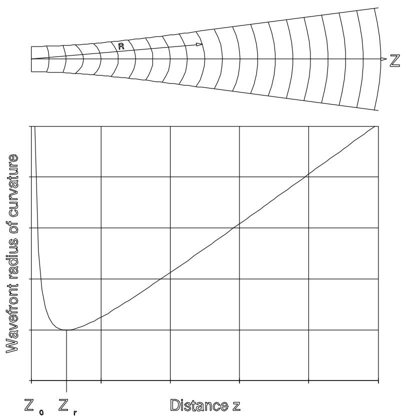

Fig. 9: Course of the radius of curvature of the wave front as a function of the distance from the waist at z=0

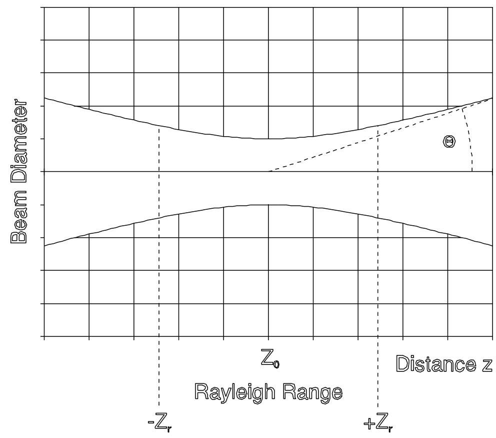

Fig. 10: Rayleigh range z_R and divergence Θ for the far field $z >> z_R$

The reason for this is that the ration of the beam diameter with respect to z has not been normalised. Let's consider, for example, a HeNe-Laser (632 nm) with a beam radius of $w_o = 1mm$ at the exit of the laser. For the Rayleigh range 2 z_r we get:

$$2 \cdot z_R = 2w_0^2 \frac{\pi}{\lambda} = 2 \cdot 10^{-6} \frac{3.14}{623 \cdot 10^{-9}} = 9,9 \text{ m}$$

To get a maximum of power into the fibre a coupling optic of focal distance f is required assuring the coupling of a Gaussian beam into a weak guiding step index fibre in the LP_{01} fundamental mode.

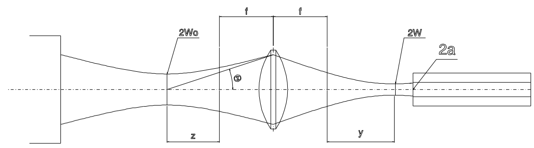

Fig. 11: For the calculation of the coupling optic

The radius at the waist is

$$w = \frac{w_0 \cdot f \cdot \theta \cdot}{\sqrt{w_0^2 + \theta^2 \cdot z^2}}$$

The position of the waist is:

$$y = \frac{z \cdot f^2}{z^2 + \left(\frac{w_0}{\theta}\right)^2}$$

Example: The beam of a HeNe laser of 0.5 mm diameter and of 1.5 mrad divergence is to focus by means of a lens. The focal distance is 50 mm and the lens is at a distance of 2 m from the laser. We find:

$$w = \frac{0,5 \cdot 10^{-3} \cdot 0,05 \cdot 1,5 \cdot 10^{-3}}{\sqrt{0,25 \cdot 10^{-6} + 2,25 \cdot 10^{-6} \cdot (2 - 0,05)^2}} = 12,6 \mu m$$

$$y = \frac{2 - 0,05 \;\; \cdot 2,5 \cdot 10^{-6}}{2 - 0,05 \;^{2} + \left(\frac{0,5}{1,5}\right)^{2}} = 1,25\mu\text{m}$$

For this example the position y of the waist coincides with the focus in good approximation and the radius of the waist is here 12.6 µm. To get the fibre under consideration adapted in an optimal way the focal distance f has to be chosen in a way that the radius of the beam is equal to the radius of the core. When laser diodes are used the preparation of the beam becomes more complicated.

2.4 Laser diodes

The laser diodes are a special class of lasers. They differ from „conventional“ lasers in two points: Laser diodes do not have any inherently defined emission wavelength, because there are no two discrete energy levels that are responsible for the laser process as with traditional lasers, but rather an energy distribution of electrons in energy bands. The second important difference concerns the propagation of the laser light within the pn zone. The spatial intensity distribution of the laser beam is defined by the laser medium and not by the resonator as for normal lasers. Generally for conventional lasers the mirrors are very large compared with the beam diameter. The laser mirror (crystal gap area of the active zone) of the laser diodes has a size of about 10 µm x 2 µm, through which the laser beam has „to squeeze“. Diffraction effects will be the consequence and lead to elliptical beam profiles.

Nevertheless, laser diodes are ideally suited for optoelectronic data transmission via fibres. They are small, cheap, easy to handle and they have a high lifetime. But most important, since the emitted light intensity is proportional to the current, the power of the diodes can be easily modulated, and therefore they are ideal for generating strings of pulses, carrying information through the fibres.

3 Experiments

3.1 Description of the modules: Basic version

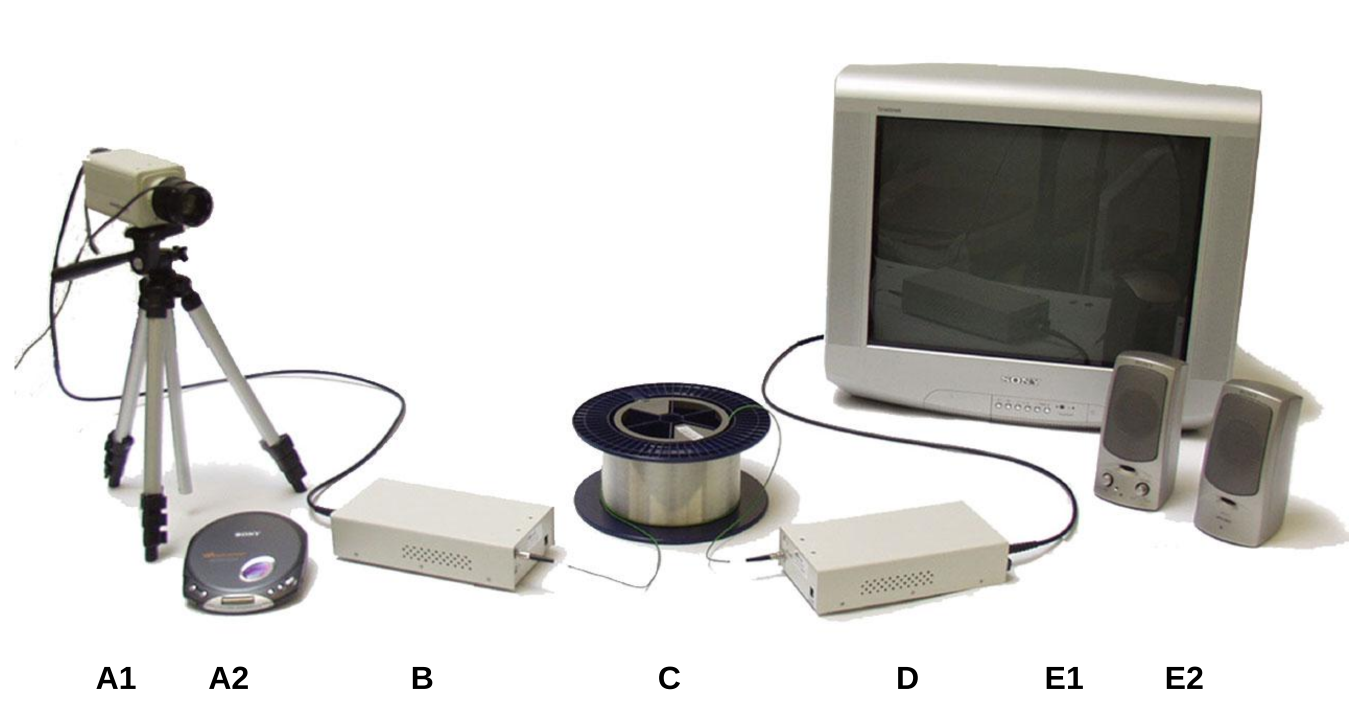

Fig. 12: Experimental set-up of the basic Data Transmission System

The video signal of the CCD camera (A1) or the audio signal of the CD player (A2) is fed to the high speed modulator of the transmitter unit (B). The modulated light of the diode laser in the transmitter unit is coupled to the 5000 m long multi-mode fibre (C) by means of an ST connector. The laser light enters the receiver unit (D) and hits a high speed photodiode from where it is fed to the amplifier. A video monitor (E1) displays the transmitted video signal, Loudspeakers (E2) play back the audio signal.

Fig. 13: Module A1 Video Camera

A colour CCD video camera with zoom objective and tripod is provided as a video source.

Fig. 14: Module A2 CD player

As audio source a CD player including a music CD is used.

Fig. 15: Module B Transmitter Unit

The transmitter unit contains a diode laser emitting at a wavelength of 1.3 µm and is equipped with a high speed modulator. Sources like CD player or CCD camera can directly be connected to this unit. At the rear panel the optical output is available at an ST connector.

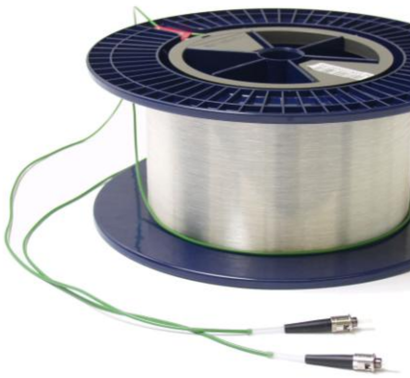

Fig. 16: Module C Optical Fibre

5000 m of a multimode fibre (50/125/250 µm) including ST connectors on both ends are used as transmission line.

Fig. 17: Module D Receiver Unit

The receiver module is provided with a fast optical detector, to which the fibre end is connected at the rear panel of this unit. Here also ST connectors are used. The video signal will be transferred by means of a BNC cable to the TV monitor, the audio signal to the loudspeakers.

Fig. 18: Module E1 Monitor

For the display of the video signal a TV monitor with scart input is used.

Fig. 19: Module E2 Loudspeakers

The playback of the audio signal is performed by a set of loudspeakers.

3.2 Experimental set-up: Basic version

Connect the video output of the camera with the video input of the transmitter unit (270TX) by a BNC cable.

One ST connector of the 5000 m transmission fibre has to be plugged in the optical TX output of the transmitter, the other ST connector in the optical RX input of the receiver unit.

Connect the video output of the receiver with the video input of the monitor by a BNC cable.

If audio signals want to be transmitted the audio connectors of the CD player and the loudspeakers have to be plugged in the audio sockets of the transmitter and receiver units, respectively.

3.3 Description of the modules: Extended version

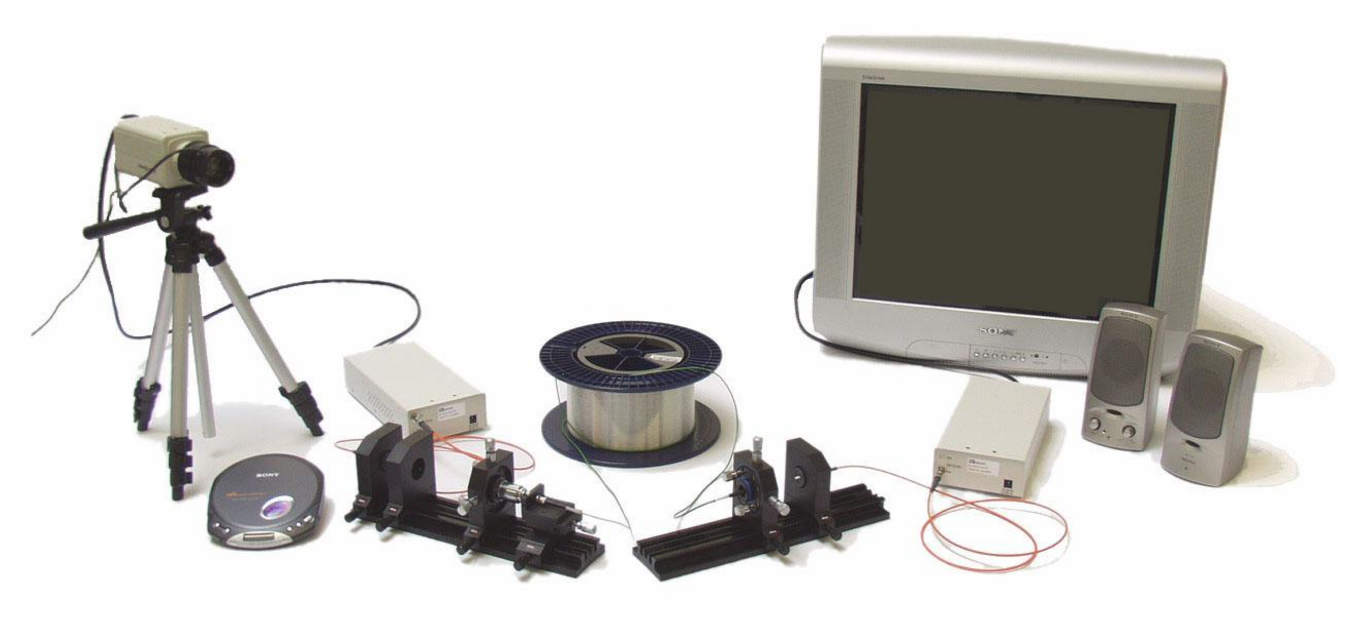

Fig. 20: Experimental set-up of the extended Data Transmission System

The basic Data Transmission System is extended by two light coupling units. They serve as input and output interfaces to and from the 5000 m transmission fibre, respectively. All modules of these units are discussed in detail in the following section. Finally, an explanation of the set up and of the modules' alignment is given.

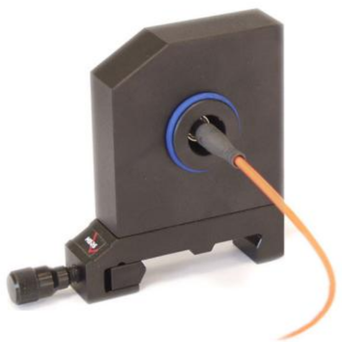

Fig. 21: Module K and P Basic fibre holder

The signal output of the transmitter unit (see chap. 3.1) is sent to the light coupling unit via a short fibre, fused to ST connectors and fixed by a mounting plate. The same mechanism builds the interface on the second coupling unit from where the light is fed in the receiver unit.

Fig. 22: Module L Collimation optics

Due to the divergence of radiation of the fibre output a collimator is necessary. An achromatic lens with a focal length of 8 mm and a numerical aperture of 0.37 is held in a mounting plate by "click mechanism" and collimates the divergent beam emitted by the fibre.

Fig. 23: Module M Focussing optics

This module has the task of focussing the collimated beam into the 5000 m long transmission fibre. A microscope objective with a numerical aperture of 0.5 and a magnification factor of 20 produces a tight focus at a distance of about 2 mm from the objective. In order to align the focus with respect to the small entry surface of the fibre (50 µm in diameter) the module possesses X,Y as well as θ,φ fine regulators.

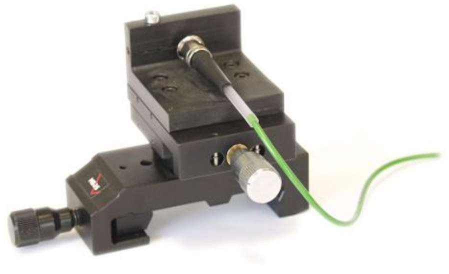

Fig. 24: Module N Fibre holder on translation stage

For regulation in Z direction the ST input connector of the transmission fibre is mounted on a translation stage. Therefore the surface of the transmission fibre can be matched to the waist of the focused beam ideally.

Fig. 25: Module O regulatory fibre holder

In the second light coupling unit no optical elements are used. The ST output connector of the transmission fibre is brought in close contact with the input connector of the receiver unit directly. The output connector is mounted on a X,Y-θ,φ mounting plate and can be translated and tilted with respect to the input connector which is fixed on Module P (see Fig. 21).

3.4 Experimental set-up: Extended version

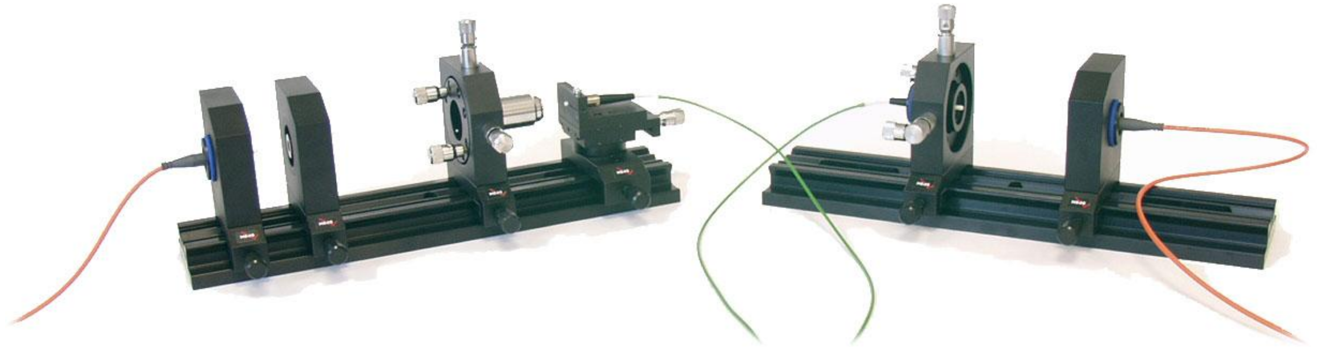

Fig. 26: Experimental set-up of the light coupling units

Set up the basic Data Transmission System according to chap. 3.1 and 3.2 and bring it to operation. Disconnect the transmission fibre input plug from the transmitter unit and plug in the ST connector of the short fibre of module K instead. Put the modules K and L in a distance of about 8 mm between ST connector and collimating lens on one end of a 300 mm rail. Put the InGaAs photodetector in its mounting plate on the other end of the rail (at the position of module N about). When the detector is connected to an oscilloscope a weak signal should be seen already. Maximize this signal by optimizing the Z position of module L with respect to module K. In the optimum position the beam is approximately collimated.

Remove the detector module and put module M and N on instead. By approaching the transmission fibre input connector on module N to the microscope objective to a distance of about 2 mm and by X and Y translation of the objective a video signal can be achieved and displayed on the monitor already. Now optimize the X,Y and the θ,φ adjustments of module M as well as the Z adjustment of module N for best signal.

Disconnect the transmission fibre output connector from the receiver unit and plug in the connector of the short fibre of module P instead. Insert the transmission fibre output plug in module O. Put the modules O and P on the second 300 mm rail. Keep a distance of about 1 to 2 mm between the two ST connectors. Optimize the video signal now by adjustment of all dimensions of module O. To control the quality of the alignment move module P away from module O. When the signal becomes worse optimize all dimensions of module O again. Try to go as far as possible with module P without loosing the video signal.