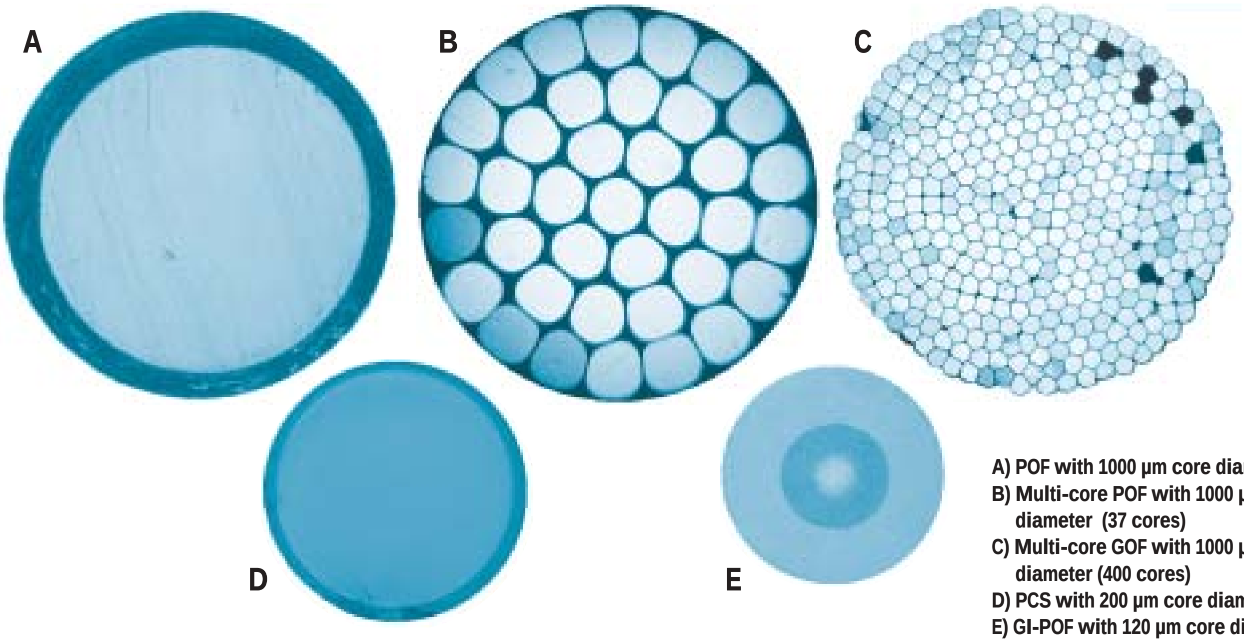

A) POF with 1000 µm core diameter
B) Multi-core POF with 1000 µm bundle diameter (37 cores)
C) Multi-core GOF with 1000 µm bundle diameter (400 cores)
D) PCS with 200 µm core diameter
E) GI-POF with 120 µm core diameter

Optical data communication over short distances

STATE OF THE ART OF FIBER TYPES, TRANSMITTERS AND RECEIVERS

Up to now, nobody used optical data transfer for short distances up to 100 m. One reason was the high effort which had to be made for connectors and another the complex set-up of the senders and receivers. New fiber types might offer better prospects.

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The data transmission over glass fibers has been state of the art in the telecommunication industry for many years. Glass fibers are also used in local networks, at least in the backbone area. But the optical data communication could not cover the application range for distances up to 100 m until now. The main reasons are the big effort for the connectors and the requirements on the mounting technology for the transmitters and receivers.

The basic idea for simplification is the use of fibers with a high diameter and easy handling. A big number of new different optical fibers, made of glass or polymers are available presently. The presented article arranges fiber types and shows the status of transmitter and receiver technology.

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Principle of light wave guiding

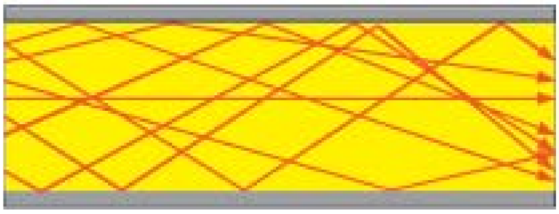
All optical fibers are based on the same principle - the optical wave guiding. The light propagates through the fiber core. In step index (SI) fibers the core is homogeneous and surrounded by a layer from a material with a lower refractive index - the fiber cladding. This layer has to be only a few micrometers thick in principle, but it will be made between 10 µm and 50 µm thick from mechanical reasons.

At the interface between core and cladding a complete reflection of the light occurs (**figure 1**), as long as the angle a_{max} is not exceeded (depending on the refractive indices of both materials).

$$\alpha_{max} = \arcsin(A_N) = \arcsin\left(\sqrt{n^2_{core} - n^2_{cladding}}\right)$$

The advantage of this fiber is that it can be manufactured easily. But an oblique launched light ray propagates through the core with the same angle all the time. This ray will arrive at the fibers output much later than a ray, propagated along the fibers axis. This effect is called modal dispersion. It limits the bandwidth of a SI type fiber to several 10 MHz (length of 100 m).

In graded index (GI) fibers however, the core is made with a continuously changing refractive index. The index is highest at the fiber axis and decreases outwards (in an ideal case it is reduces proportional to the radius squared). As shown in **figure 2**, the rays are deflected all the time in the fiber center direction and guided in the core with this effect. A reflection at the cladding is not required. The rays propagate outwards a bit faster, that is why the mean propagation speed of all light paths is nearly the same. Mode dispersion is more or less eliminated. GI fibers allow much higher transmission rates, compared to SI fibers, but will be more difficult to manufacture, because the material composition has to be changed in dependence of the radius gradually.



Step index profile: high refractive index in the whole core, smaller refractive index in the optical cladding, light rays will be totally reflected at the cladding

1 **The principle of step index wave-guides**

Attenuation and numerical aperture

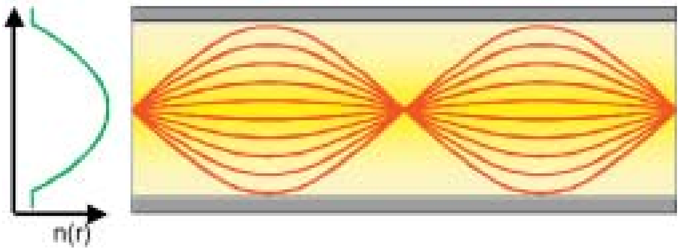
The most important parameter of an optical fiber is the attenuation. It is given in dB/km and describes how much an optical signal is reduced per kilometer of the fiber. Typical transmission systems can work error free with a loss of about 20 dB to 30 dB. But this includes losses at the launch into the fiber and the output, as well as on bends and connectors. The attenuation of optical fibers is wavelength dependent. The Numerical Aperture (NA) is determined by the difference between the refractive indices of the core and the cladding. A high NA (corresponding with high possible propagation angles) makes the light launch into the fiber easier and reduces the additional loss at fiber bends, but also increases the mode dispersion too. The bandwidth of the fiber is given by the highest possible propagation time differences, thus by the NA and the used index profile. For Si and GI fibers we have:

$$\text{bandwidth (SI)} = \frac{0.44}{\Delta t} = \frac{0.88 \cdot c \cdot n_{core}}{L \cdot A_N^2}$$

$$\text{bandwidth (GI)} \approx \frac{3.5 \cdot c \cdot n^3_{core}}{L \cdot A_N^4}$$

At a NA of 0.37 a SI type fiber has a bandwidth of 29 MHz·100 m for example, whereas a GI fiber has 1.891 MHz·100 m. Effects like mode mixing and angle dependent losses increase the bandwidth in most cases. The core diameter does not have any effect, as expected sometimes.

Besides the highly different core diameters, the index difference is changed and with this, as described above, the maximum guided light angle. **Figure 3** shows the profile of the standard SI POF with 1 mm core diameter and AN of 0.50. This fiber is used in car networks and automation for example. Beside this, a graded index fiber with again approx. 1 mm core diameter is to be seen. Thanks to the GI profile, the bandwidth of this fiber is much higher than for the SI fiber.



Graded index profile: high refractive index in the center, reduced outwards, rays are inflected continuously

2 **Principle of the graded index profile fiber**

Index profiles and materials

Figure 4 compares the index profiles of different glass fibers and one GI polymer fiber. Graded index profile POF will be made with a typical core diameter of 120 µm today. The smaller diameter makes the handling more difficult than for 1 mm fibers, but enables the use of transmitters and receivers of existing glass fiber solutions.

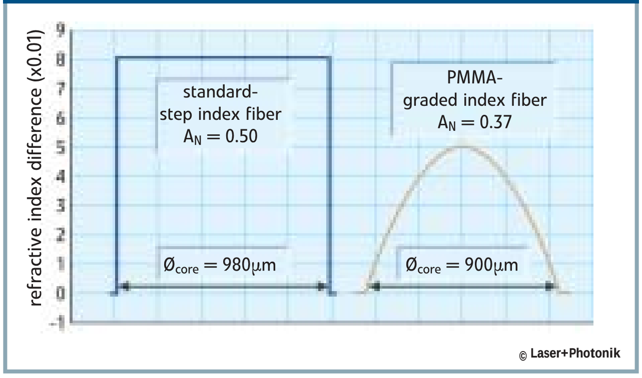
The index profiles of the classical glass fibers are shown on the right side. The single mode fiber has a core diameter of only 10 µm. That means, that all connectors and couplings to active components must be made with tolerances of less than 1 µm. The small NA requires high parallelism of the fiber axis at couplings. In the field of short distance data communication the single mode fiber is used for extremely high quality demands only.

Graded index profile GOF is successfully used in the area of local computer networks (LAN) for a number of years. Fibers with a core diameter of 62.5 µm are used in the US and with 50 µm core diameter in most of the other countries. With a data rate of 1 Gbit/s a distance of several 100 m can be bridged.

For low data rate applications (5 Mbit/s) and long distances at the same time, where the bandwidth does not play a role, the PCS (Polymer Clad Silica) was developed. A core from pure silica glass (200 µm) is surrounded by a thin polymer cladding (15 µm). The large NA limits the bandwidth, but allows narrow bands and simple couplings. One manufacturer offers a PCS with a semi GI profile. The bandwidth can be increased dramatically, as long the transmitter launches the light well collimated into the fiber.

The cross-areas of some of these fibers are shown in the **title figure**. POF as well as GOF can be made as bundles. The advantage of a bundle is, that even with ▶

Index profiles of polymer fibers



3 SI compared to GI fibre

smaller NA (corresponding to larger bandwidth) small bending radii are possible.

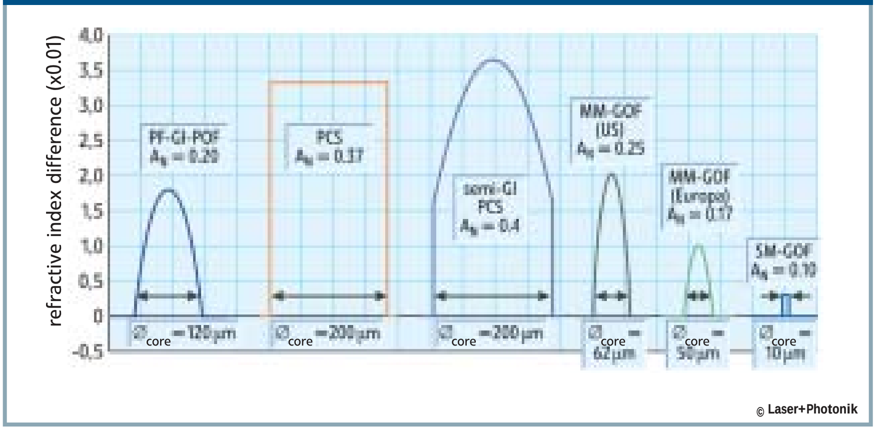
Losses in optical fibers and optical windows

Depending on the materials used, fibers show different attenuation characteristics. It is common for all fibers that the attenuation strongly depends of the wavelength. One of the basic processes is the Rayleigh scattering. It causes the fact, that in glass as well as in polymers the short wavelengths are more attenuated than the longer ones. This leads to the assumption, that one only has to work at sufficient long wavelengths to have a low loss system. Nevertheless, there are losses due to the chemical bonds between the atoms in all materials. This effect is expressed by small ranges of increased attenuation in the loss spectrum. The higher the atom mass, the longer the wavelengths of the loss peaks.

Polymers contain a lot of Hydrogen. That's why the absorption bands occur even in the visible spectral range. The losses of a PMMA fiber (standard material for SI POF) are shown in **figure 5**. The lowest attenuation values are at 520, 570 and 650 nm wavelength. In order to reduce the losses in polymers, the hydrogen must be substituted by a heavier element. A good practical solution is Flour (one well known Flour polymer is Teflon). In theory the losses can be reduces to less than 1 dB/km with such materials. The best values for realized fibers are a little less then 10 dB/km, as shown in **figure 6**. Because there is also Rayleigh scattering in these fibers, the smallest attenuation values are at longer wavelength in the range of 800 to 1,300 nm, approximately. In silica glass there are only Silicon Oxygen bonds. Even from approximately 1,600 nm wavelength the bond absorption plays a roll here. In theory the lowest attenuation is 0.16 dB/km at 1,550 nm wavelength, as illustrated in **figure 7**. The significant loss increase around 1,380 nm is caused by remaining water (OH ions to be more precise). It can be suppressed by modern production technology. The refractive index difference is made in SiO_2 fibers by substitution of some percent of Silicon by Germanium in the core area. There is nearly no additional loss caused by this substitution.

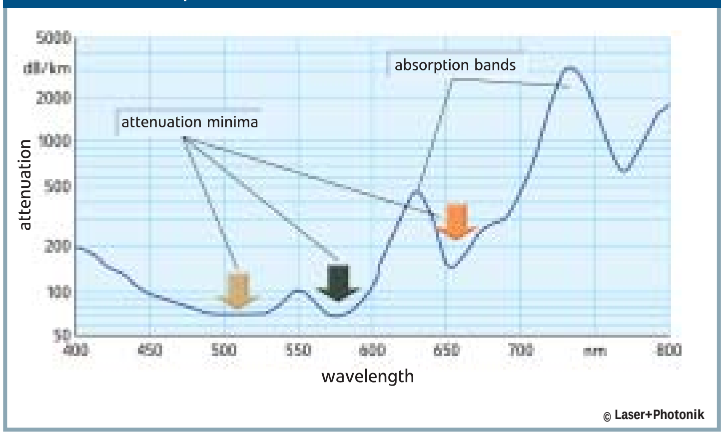
The losses of the PCS fiber are shown in **figure 7**. The core consists of SiO_2, but the cladding causes higher losses (depending on the material), but always much smaller compared with pure POF.

Index profiles of different glass optical fibers



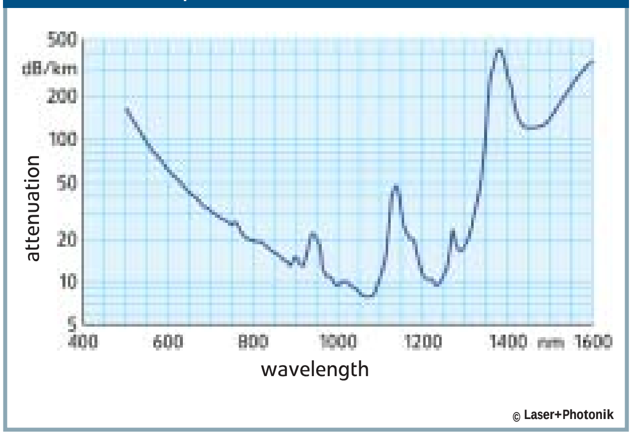
4 GI-POF compared to several glass optical fibres

Attenuation spectrum of the PMMA-POF



5 Losses in a PMMA fibre

Attenuation spectrum of POF



6 Losses in fluorinated polymers (asahi glass)

LEDs and Laser Diodes

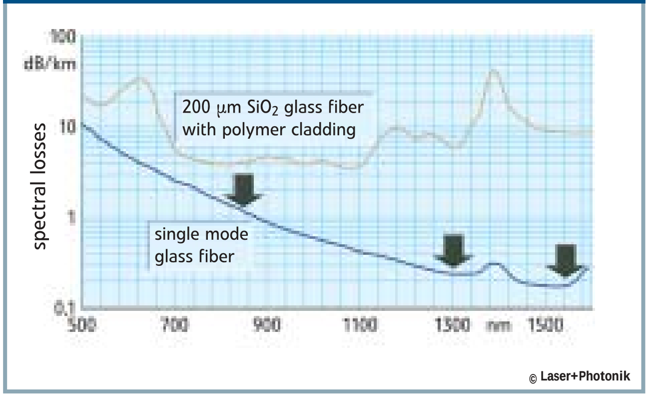
Not only fibers, but also optical electrical converters are required for a data transmission. The sources should not be bigger than the fiber and transmit the light in an angle range, guided by the fiber. Often one needs lenses or parabolic mirrors for a better coupling into the fiber. For the photo detectors the corresponding requirements are valid.

LEDs (light emitting diodes) are large area emitting components, which are available at all wavelengths. Due to its large area (corresponding to high electrical capacity) they cannot be modulated very fast. LEDs are low cost and simple to use. The combination with the SI-POF is nearly perfect.

RC-LEDs (resonant cavity LEDs) are different from conventional LEDs due to the two additional semiconductor Bragg mirrors above and below the light generation layer. Presently they are available in the 650 nm wavelength range. They will be available with 520 nm soon. Caused by the special design they allow higher modulation speed and better coupling into the fiber. RC-LED are used for example in car networks.

LDs (conventional laser diodes) emit collimated light from the edge (edge emitters). They are available starting from 635 nm wavelength. Laser diodes are very fast, but they operate only until a given current (the so called threshold current), which is changing strongly with the temperature moreover. For the operation in data communication a power control is required, which makes the components more difficult.

Loss spectrum of a $SiO_{2\,g}$ glass fibre



7 **SiO2 glass fibre with and without polymer coating**

Vertical-Cavity-Surface-Emitting-Laser (VCSEL), so called surface emitters radiated like LEDs from the upper surface. But the light is collimated like for lasers (better fitted to the fiber NA). There is a threshold current, but a very small one (typically a few milliamps). High performance and low cost VCSEL are available at 850 nm wavelengths. They are fast and easy to use. At 650 nm the VCSEL suffer from a to big power drop at higher temperatures, even at 50 °C.

Tables A and **B** list the parameters of sources and its possible combination with fibers. More or less all fibers can be used at 650 nm and different transmitters are available. The only missing component is a source for the Gbit/s-range, which can be used for up to +70°C. ▶

VCSEL at 850 nm are the perfect transmitters for Gbit/s-rates. They can be used with SI-PCS, PF-GI-POF and also with conventional GI-MM glass fibers. Moreover they allow operation temperatures of up to 125°C. For short distances (< 5 m) 850 nm VCSEL can be combined with PMMA-POF too, for example in parallel data communication between computer components and integrated circuits.

Capacities and applications

At low data rates in the upper Mbit/s range, optical transmission systems are limited by the fiber attenuation in most cases. For modern applications the limitation by the bandwidth becomes more and more important, at least for the step index fibers. An overview of possible data rates and distances can be found in [2] and [3]. Here a few examples:

The SI-PMMA-POF can be used for the transmission of up to 125 Mbit/s over 100 m (red or green LED). 1 Gbit/s transmission is possible over short distances of 10 to 20 m. GI-PMMA-POF allows the same distances but enable 1 Gbit/s still at 100 m. The best reported results using PF-GI-POF are the transmission of Gigabit Ethernet (1.25 Gbit/s) over 1 km and of 10 Gbit/s over 100 m [4, 5].

The SI-PCS allows the transmission of up to 200 Mbit/s over 100 m too, and correspondingly more over shorter distances. Multi core POF enables nearly the same bandwidth as GI PMMA POF, whereas the multi core glass fiber is comparable with the SI PMMA POF. For multimode glass fiber there are different limits valid, depending in the fiber quality. Originally, the fiber was designed for Gigabit Ethernet over distances of 200 m to 500 m. With the newest versions (OM-3) the transmission of 10 Gbit/s over 500 m is possible (using 850 nm VCSEL).

There are no hard bit rate limits in principle. With electrical compensation after the receiver or with the selective suppression of modes with very high propagation time differences (off-axis launch for GI-GOF) the bit rate can be increased drastically. Modern copper data cable has only some MHZ-bandwidth, they reach the high transmission capacity only with the electronically signal processing. Such methods are economic only for huge volumes, which are not yet realized in the field of optical communication. But there is a lot remaining potential for further performance improvements for the above-described fibers.

Parameter	LED	LD	VCSEL	RC LED
wavelengths	all	> 630 nm	> 660 nm	650 nm
threshold current I_{th}	-	40 mA	8 mA	-
typ. optical output power	2 mW	7 mW	1 mW	2 mW
modulation data rate	250 Mbit/s	> 4 Gbit/s	> 2 Gbit/s	500 Mbit/s
spectral width [nm]	30	2	3	10
$\Delta\lambda/\Delta T$ [nm/K]	0,12	0,18	0,06	0,08
$\Delta P_{opt}/\Delta T$ [dB/K]	0,02	0,02	0,08	0,03
emission angle [°]	50	60 x 8	10	8
emission area [µm²]	200 x 200	3 x 0,3	10 x 10	30 x 30
remarks	low cost	requires current control	at 650 nm only for +50° C	in laboratory also für 520 nm

A Parameters of sources for short distance communication (typical values)

LED	source	maximum bit rate Mbit/s	1000 µm PMMA SI-POF	900 µm PMMA GI-POF	120 µm PF GSI-POF	200 µm SI PCS	1000 µm MC GOF
450	LED	250	✓				
250	LED	250	✓			✓	
650	LED	250	✓	✓		✓	✓
	RC-LED	1,000	✓	✓	✓	✓	✓
	VCSEL	5,000	✓	✓	✓	✓	✓
	LD	2,000	✓	✓	✓	✓	✓
850	LED	250				✓	✓
	VCSEL	10,000			✓	✓	✓
1300	VCSEL	10,000			✓		
	LD	10,000			✓		

B Possible combinations of optical sources and fibers

Usage for short distances

In automation the PMMA-POF and the SI-POF are in use successfully for a number of years. Data rate of up to 12 Mbit/s are possible in the different field bus standards. The maximum transmission distance is limited to about 70 m using POF and several 100 m with PCS. The systems will base on Fast Ethernet (125 Mbit/s) more and more in future.

One of the most important applications of optical short distance transmission systems is in car networks presently. As the first car manufacturer DaimlerChrysler introduced an optical network with the D2B (Digital Domestic Bus).

Different car manufacturers use the international standardized MOST system (Media Oriented System Transport) since 2001. The data rate of 25 Mbit/s allows the connection of audio, video and data components (navigation systems). More than 30 series are equipped with MOST today. Infineon alone delivered 18 million transceivers in 2004. The A-, M-, E, and S-classes of Mercedes and the 1-, 5- and 7-series by BMW are running with such a system. With the Byteflight system BMW uses the

POF for optical busses as well in security systems, e.g. the airbag control.

All actual car networks work with red LED/RC-LED and PMMA-POF. The usability of MC-POF and SI-PCS is under investigation at this time. Very important is the expansion of the operation temperature range (engine compartment).

Probably the most interesting field of application for the optical short distance communication is home networking. Millions of people own glass fiber access with 100 Mbit/s or already 1 Gbit/s in Asia. The development will start in the next years in Europe too. Radio networks alone will not be sufficient to deliver the data to the end user devices. That's why fast and easy to install data lines will be required as well. Especially the POF is a favorite option for this purpose. A Fast-Ethernet cabling solution is just offered by the company Die-Mount, where the POF can be simple cut and screwed at the transceiver [6].

Summary: Germany has a good chance

In total, the optical short distance data communication owns a variety of future application areas. Besides the above described example, one can add sensing and multi parallel connections, like in computers. Continuous progress will be made on fiber development as well as for semiconductor components. Optical connection is not only simpler in most cases, but also more secure, less weight and smaller. Germany is still leading in this technology; hopefully we can use the market potential.

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