

# Specialty fibres for light transmission from UV to IR

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The transmission properties of a glass fibre are predominantly determined by its content of hydroxide ions (OH<sup>-</sup>). Fibres with a high OH-content feature very good transmission in the UV range, whereas the IR-transmission is limited by OH-absorption bands. In contrast, fibres with low OH-content transmit infrared light well, but often have undesirable absorption bands in the UV. This article illustrates how the properties of the core material influence potential applications of a glass fibre in different wavelength ranges.

The transmission of light in an optical waveguide is based on the physical principle of total internal reflection. If light is reflected at an optically rarer medium under certain angle dependent conditions, the light can be guided nearly without losses. In doing so, a small part of the light, the so-called evanescent field, penetrates the optically rarer material. All waveguides have to be composed of at least two materials in order to guide light without loss, namely the fibre core and the cladding, with different refractive indices. For the condition of total reflectance the core needs to have a higher refractive index than the cladding. It is important to have a fibre design with two different types of fused silica glass, as compared to plastic clad fibres the optical attenuation with a glass cladding is still low.

Light can propagate in a glass fibre in different modes<sup>1</sup>, these modes having different transit times in the fibre due to so-called mode dispersion. For high transfer rates in telecommunications it is mostly important to transmit the light only in the fundamental mode. For that purpose silica fibres are constructed with a very small core (8 µm) and a large cladding diameter (125 µm). The requisite refractive index step between cladding and core can be set in these types of fibres for example by using a germanium doped fused silica core and an un-doped fused silica cladding (figure 1).

In many glass fibre applications for high power light transmission it is not important to guide the light in the fundamental mode, rather the aim is to transmit as much light power as possible. Hence, so-called multi-mode optical fibres are utilised, these being able to transmit "higher"

optical modes. Such multi-mode step-index fibres exhibit a by far larger core diameter than single-mode fibres. Thereby the refractive index of the cladding (figure 1) is lowered with respect to the un-doped fused silica core e.g. by doping with fluorine (F).

Important factors which influence the transmission properties of a fibre are its geometry (see section 2.1) and the numerical aperture (see section 2.2). Numerical aperture describes the maximum incident angle at which light can be coupled into a fibre with respect to the optical axes and still be guided. The transmission properties of a fibre are in particular determined by the core material chosen, which is based on a high purity synthetic fused silica (see section 2.3).

## 1 Production process of multi-mode step-index fibres

Glass fibres are drawn from preforms, these preforms having the same material content and the same cladding-core geometry as the final glass fibre – with the exception that the diameter of the core and the cladding assembly is several hundred times bigger in the preform. The fibre, with a typical outer diameter between 100 and 1000 µm, is drawn from the preform in a fibre drawing furnace at temperatures above 2000°C.

The refractive index step between core and cladding glass, essential for total reflectance, can be set in different ways during the preform production. Doping the

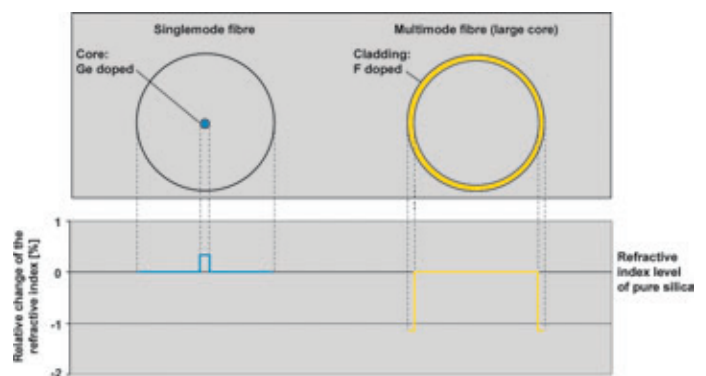
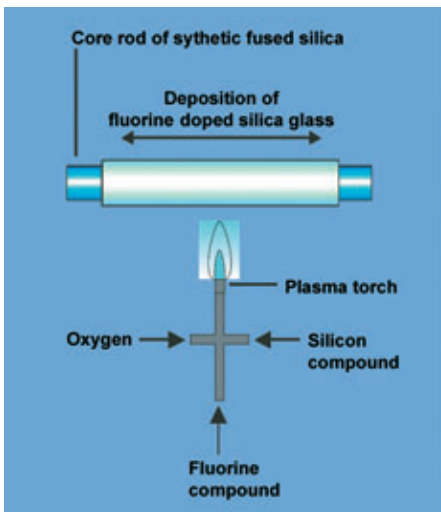


Figure 1: Cross-section and refractive index profile of step-index fibres

core material with e.g. germanium or phosphorus increases the refractive index of the core material but introduces additional absorption bands that can limit the spectral range of applications for the fibre. Alternatively, the cladding can be doped with fluorine or boron, lowering its refractive index (see figure 1). A combination of both methods is also possible in order to realise higher refractive index steps.

There are many preform production processes [1], although most of them are unsuitable for the incorporation of a high fluorine content in the cladding glass – the exception here being plasma outside deposition (POD). In POD, plasma torches prepare the reaction compounds from oxygen and gaseous compounds containing silicon and fluorine. Fluorine doped fused silica nano-particles are thus deposited layer by layer onto rods of extremely pure synthetic fused silica and are directly vitrified (figure 2). The non-equilibrium condition during the deposition process allows very high fluorine concentration in the fibre cladding, the fluorine doping level being set by the mixture ratio of the reactants and other process parameters. These fibres are often called silica-silica multi-mode

<sup>1</sup> Modes are possible angle-dependent Eigenstates of the light propagation in a waveguide, and result from the wave properties of light.



**Figure 2:** Production of fibre preforms via plasma outside deposition (POD)



values in excess of 0.28 can be realised depending on the fluorine concentration of the cladding. Hence acceptance angles up to  $16^\circ$  are possible.

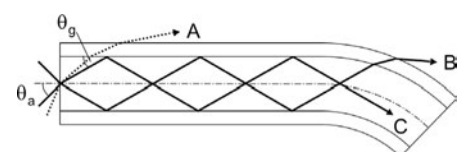
For a bent fibre with sufficiently high curvature, the angle of incidence for guided light can locally exceed the critical angle, coupling light out of the core and into the cladding (see figure 4). An alternative approach to understanding this loss mechanism can be made by considering the distorted shape of the mode at the bend in the fibre. As the evanescent field penetrates deeper into the cladding on the outside edge of high curvature bends, attenuation as discussed previously increases locally. This effect can be minimised by reducing bend curvature in the fibre or by increasing the NA [3].

## 2.3 Fibre attenuation

The attenuation  $A$  in an optical fibre is a measure of the absorbed light intensity. Reasons for the attenuation are e.g., absorption of the quartz material, light scattering, leaking of modes as well as losses caused by micro- and macro-bending. While attenuation  $A$  is indicated in dB, the attenuation coefficient  $\alpha$  results from the attenuation  $A$  per fibre length  $L$ . To measure  $\alpha$ , light with the intensity  $I_0$  is coupled into a fibre with a length of  $L$ , and the transmitted light intensity  $I_L$  is measured. Neglecting insertion losses,  $\alpha$  is thus defined as [4]:

$$\alpha [dB/m] = \frac{A}{L} = \frac{10 \cdot \log(I_0/I_L)}{L} \quad (\text{Eq. 2})$$

There is background attenuation (see theoretical limit, figure 5) even at ideal light transmission conditions. The reason for the attenuation in the UV range is Rayleigh scattering in the amorphous glass, which is reciprocally proportional to the fourth power of the incident wavelength ( $1/\lambda^4$ ). The increase in the background attenuation



**Figure 4:** Acceptance angle and optical path within a bent fibre. Beam A is coupled into the fibre with an incident angle larger than the acceptance angle  $\theta_a$  and the requirement for total reflection within the fibre is no longer fulfilled, resulting in leakage into the cladding. Beam B, initially properly confined, is lost to the cladding in the region of a sharp bend – the sharp bend resembles an effective local reduction in the NA. Beam C fulfils the requirements for continued guidance

step-index fibres, or large core fibres. The refractive index decreases step-like from core to cladding – refractive index differences of  $28 \cdot 10^{-3}$  can be realised depending on the doping level (typically about 5 - 8 mol%), corresponding to numerical apertures of up to 0.284 (see section 2.2).

## 2 Optical properties

### 2.1 Cladding to core diameter ratio

By total internal reflection in an optical fibre the evanescent field penetrates into the fibre cladding immediately adjacent to the core, the amplitude of the evanescent field decaying exponentially outwards. If the cladding is too thin, an undesirably high fraction of the evanescent field can couple out of the fibre cladding, leading to an additional attenuation of the light wave due to this lost fraction. If the major fraction of the evanescent field remains in the cladding this effect is lower and negligible. Longer wavelengths penetrate deeper into the cladding, and as a rule of thumb, the cladding thickness should be at least ten times the wavelength of the guided light to minimise these attenuation effects. This type of attenuation is uncritical for shorter fibre lengths and the cladding can be made thinner as needed.

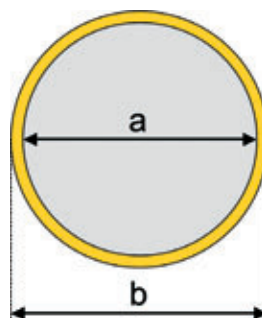
The cladding to core diameter ratio (CCDR) is a good parameter for characterising the geometry of preforms and fibres. For cladding diameter  $b$  and the core diameter  $a$ , the CCDR is  $b/a$  (figure 3). Typical CCDR-values for large core fibres vary between 1.04 and 1.4, and compare to about 15 for single-mode fibres<sup>2</sup>.

### 2.2 Numerical aperture

Total internal reflection occurs at any interface moving from an optically rarer to an optically denser medium, but only up to a maximum critical incident angle  $\theta_c$ . If the light is incident at the interface at a steeper angle than this critical angle, a fraction of the light can couple across the interface. For light guided in a fibre, the angle of incidence at the interface between core and cladding correlates with the light input angle into the fibre by Snell's law of refraction. This results in an acceptance angle  $\theta_a$  for fibres, defining the maximum input angle for light relative to the optical axes that will be properly guided (figure 4). The sine of this angle is furthermore called the numerical aperture (NA), where the acceptance angle and thus the NA are determined by the refractive indices of the core ( $n_1$ ) and the cladding ( $n_2$ ):

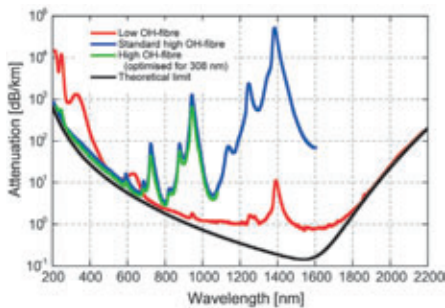
$$NA = \sin \theta_a = \sqrt{n_k^2 - n_M^2} \quad (\text{Eq. 1})$$

If the light is coupled into the fibre from a medium other than air, one has to divide by the refractive index of the medium. Un-doped quartz has a refractive index of 1.457 at 633 nm. The standard value of the NA at this wavelength is 0.22. NA



**Figure 3:** Definition of the cladding to core diameter ratio (CCDR), here for a large core fibre

<sup>2</sup> e.g., typical cladding diameter of 125  $\mu\text{m}$  and core diameter of 8.5  $\mu\text{m}$   $\Rightarrow$  CCDR =  $125/8.5 = 14.7$ .



**Figure 5:** Attenuation spectra for different large core fibres

above 1550 nm is caused by the excitation of phonons in the fused silica glass [2].

The transmission properties of glass fibres are mainly determined by the optical properties of the core material. For example, transmission in the IR range is reduced by the OH-absorption band at 2720 nm as well as higher harmonics at 2220, 1380, 1240, 940 and 720 nm [5]. The higher the OH-content<sup>3</sup> in the fibre, the stronger the attenuation in the IR range. Fibres with a “high” OH-content (approx. 700 ppm), so called “high OH-fibres”, do however show excellent transmission properties in the UV range (see standard high OH-fibre, figure 5).

Fibres with a low OH-content (<1 ppm) typically feature excellent transmission properties in the visible as well as in the near infrared range. But these so-called “low OH-fibres” generally show additional intrinsic defect bands in the UV range (figure 5), caused either by a lack of OH-molecules in the fused silica matrix or by the introduction of chlorine during production of the core glass [6].

Besides the standard high OH-fibres further specialty fibre types optimised for UV-applications are available. For example, fibres with low background attenuation at 308 nm are well suited for the transmission of XeCl excimer laser light (see at 308 nm opti-

mised high-OH-fibre, figure 5). Although the majority of fibre core material exhibits photo-degradation through absorption of UV wavelengths (<250 nm) [6], the glass matrix can be optimised for UV applications by minimising this issue. This type of fibre shows an overall attenuation spectra very similar to standard high OH-fibres.

No single fibre ideally covers the wavelength range from 190 nm up to 2200 nm, and fibre thus needs to be chosen to suit a specific task. Besides the core material the fibre cladding can also affect the transmission properties of glass fibres. Silica fibres can also be plastic clad (plastic clad silica, PCS), but this type of fibre shows strong additional attenuation [2].

### 3 Typical applications for large core fibres

Large core fibres are used for diverse applications, for instance, to transmit high laser powers for laser cutting and welding (figure 6) and similarly for coupling the pump light source to the laser active medium of Nd:YAG rod lasers or fibre lasers. High power fibres additionally find uses in medical applications, for example for removing arterial blockages with laser radiation (figure 7) or for vaporising abnormal enlarged prostate tissue. Another important application area is in optical spectroscopy, where the fibres are used to carry light (UV to IR) without loss to a spectrometer. Single fibres can also be bundled for a range of applications, including UV curing of reticulating adhesives or light source homogenisation in photo-lithographic applications.

### 4 Summary

The optical properties of fused silica fibres are influenced by different factors such as the chosen core material, the specified CCDD and numerical aperture. Fused silica fibres can thus be designed with optimal transmission properties for diverse application areas including medical technology, materials processing, the automotive industry or spectroscopy.



**Figure 6:** Materials processing, here in the automotive industry (image courtesy of Trumpf Laser GmbH & Co. KG)

### Literature:

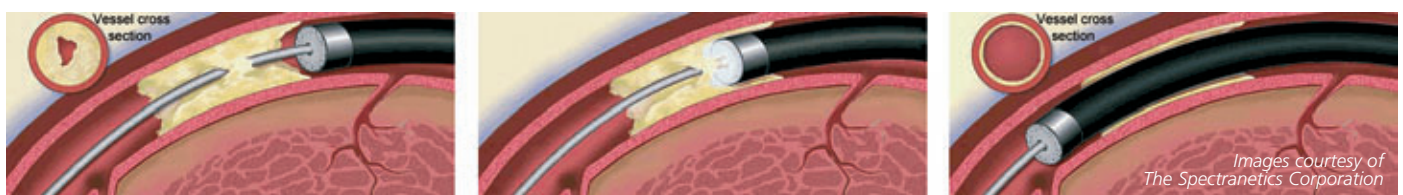
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<sup>3</sup> Instead of “OH-content” often the colloquial term “water content” is used even though only OH-groups are implanted in the fused silica matrix. The OH-absorption is caused by the excitation of a vibrational stretch mode of OH-molecules.



**Figure 7:** Removal of arterial blockages by excimer laser angioplasty. First of all a laser catheter is inserted into the blood vessel via a guide wire. Pulses of ultraviolet (cold) excimer radiation are transmitted through the circular arranged fibre bundle to enable a precise ablation of the blockage. For a better visualisation the depth of ablation is displayed enlarged – in reality the depth is about 40 µm from the front end of the catheter. The catheter advances slowly through the blockage vaporising the plaque. If necessary a subsequent balloon dilatation can improve the results of the procedure