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New Silica Fiber for Broad-Band Spectroscopy

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Abstract. Optical fibers used in spectroscopic applications have been limited by the ability of silica fibers to transmit well from the UV through the IR. High-OH fibers have high transmission in the UV but the IR transmission is limited by OH absorption bands. Low-OH fibers show UV absorption. The causes for transmission losses in all silica fibers, especially the UV absorption, will be discussed. A newly available silica glass with good transmission from the UV through the IR for astronomical broad-band spectroscopy applications will be presented.

1. Introduction

Multi-object spectroscopy with optical fibers at large field-of-view telescopes requires high fiber transmission typically in the spectral range between 350 and 1000 nm, and sometimes up to 2000 nm. The most important factor for transmission is the fiber material. Among the different types of fibers, all-silica fibers provide the highest transmission in this range; nevertheless, the transmission is restricted by the OH absorption bands with a fundamental absorption at 2722 nm and the corresponding higher-order bands at 2212, 1383, 1246, 925, and 724 nm (Humbach 1996). In order to avoid the negative influence of these OH bands, fibers with an OH content of only several ppm have to be used. Unfortunately, the UV transmission of such a fiber is lower than in fibers with high OH content.

All optical fibers consist of a core and an outer cladding, where the cladding has a lower index of refraction than the core. This geometry is essential for waveguiding, since the propagating wave is totally reflected at the interface between core and cladding.

All silica fibers are typically produced in a two-step process. In the first step, a preform with a diameter of several centimeters is produced; this is then drawn into a fiber in the second step. Different preform production methods are reviewed by Koel (1983). The plasma outside deposition (POD) process used at Heraeus Quarzglas for the production of preforms for multimode fibers will be explained in the next section. In §3 the factors that affect the optical properties of a multimode fiber including the cladding-to-core diameter ratio (CCDR), the refractive-index difference and the core material are discussed. In §4 a newly available fiber with good transmission from the UV through the IR is discussed, and in §5 recommendations for choosing the appropriate fiber for different spectral regions of interest are given.

2. Production of All-Silica Multimode Fibers

The production of all-silica fibers starts with the manufacturing of preforms which have the same CCDR value and refractive-index step as the final fiber, but an outer diameter of several centimeters.

In principle there are several ways of producing a refractive-index step in an all-silica fiber: 1) doping the core material (e.g. with Ge or P) to increase refractive index relative to undoped silica; 2) doping the cladding (e.g. with F or B) to decrease the refractive index relative to undoped silica; and 3) a combination of 1) and 2).

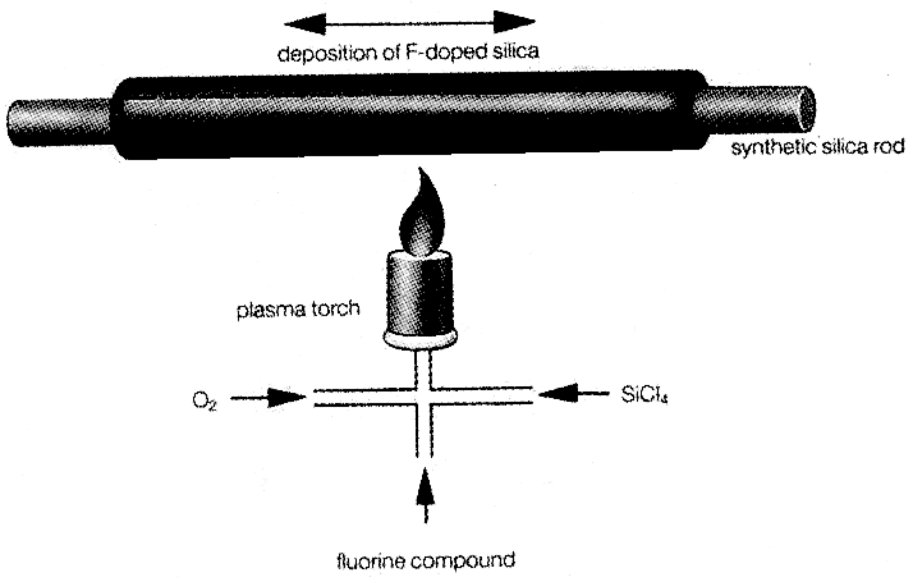

Figure 1. Deposition of a fluorine-doped cladding layer.

Preforms can be fabricated by a variety of techniques (Koel 1983). The most common methods for preform production are modified chemical vapor deposition (MCVD), vapor-phase axial deposition (VAD), and outside vapor deposition (OVD). The method which is used for the production of the Heraeus Fluosil preforms is a modification of the OVD method. The preforms are manufactured by the plasma outside deposition process. Rods of extremely pure synthetic fused silica are coated with fluorine doped silica layers (see Fig. 1) to obtain preforms with step-like refractive-index profiles. Strong thermal gradients combined with the high temperature plasma lead to chemical-deposition conditions, which allow very high fluorine concentrations to be incorporated in the fused silica network. Refractive-index differences of 0.027, corresponding to numerical apertures in excess of 0.28, have been realised.

A Fluosil preform is manufactured as a large ingot which is pulled and cut to yield rods suitable for fiber drawing. A sample fiber is drawn from every manufactured ingot to determine the attenuation by the cut-back method.

3. Optical Properties of Fibers

The fiber characteristics which determine their optical properties, and in particular, their transmission losses will be discussed in this section. For an introduction to fiber optics see also (Nelson 1988).

3.1. Cladding/Core Diameter Ratio

The guided light in an optical fiber is totally reflected at the core/cladding interface. At every reflection a small amount of the light intensity penetrates into the cladding (evanescent field). In the case of a thin cladding, the evanescent field can reach the outer diameter of the fiber, thus leading to outcoupling and hence to attenuation of the guided wave. The cladding thickness relative to the core is given by the cladding-to-core diameter ratio, which is defined as the ratio of the outer preform diameter b and the core diameter a: CCDR $= b/a$ (see Fig. 2.

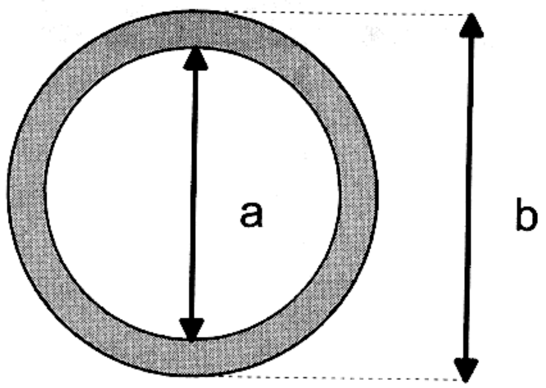

Figure 2. Definition of cladding/core diameter ratio (CCDR).

Figure 3 shows the attenuation spectra of two low-OH fibers (Fluosil SWU), both with a core diameter of 200 μm but with different cladding thicknesses. The CCDR values of the two SWU fibers are 1.1 and 1.2. The attenuation K, in dB is linearly proportional to the fiber length and is commonly used to describe telecommunication fiber. It is defined as:

$$K[\text{dB}] = -10 \cdot \log T,$$

where T is the transmission of the fiber. The transmission of a fiber with an attenuation of 10 dB km^{-1} is 10% after 1 km of fiber length.

The additional losses at higher wavelengths in the SWU1.1 fiber compared to the SWU1.2 fiber are due to the higher guiding losses with the smaller cladding thickness. As a rule of thumb, the cladding thickness should be at least ten times the wavelength of the guided light to avoid significant losses. As an example, for

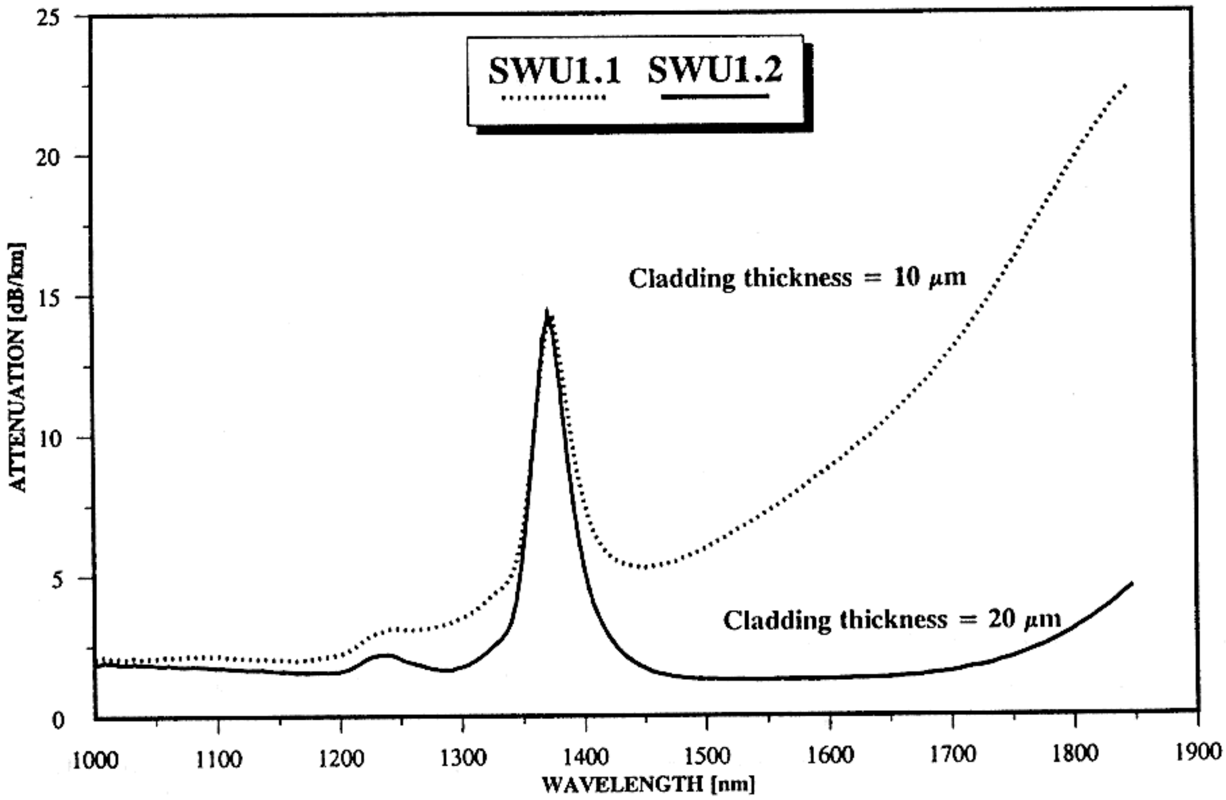

Figure 3. Transmission of fibers with different cladding thicknesses.

the transmission of light with the wavelength of 1 μm in a fiber with 200 μm core diameter the CCDR value should not be less than 1.1. The validity of this rule can be seen in Figure 3. For wavelengths up to around 1 μm the attenuation of both fibers is the same, but for longer wavelengths additional losses are observed in the SWU1.1 fiber, which has a cladding thickness of 10 μm.

3.2. Refractive-Index Difference

The refractive index difference of a step-index fiber defines the numerical aperture, NA, of the fiber. The acceptance-cone half angle, Θ, is defined as:

$$\sin\Theta = NA = \sqrt{n_1^2 - n_2^2},$$

where n_1 and n_2 denote the refractive indices of the core, and the cladding material respectively. A typical value for the refractive-index difference of a Fluosil all-silica fiber is $\Delta n = 0.017$, which corresponds to an NA of 0.22. The value is defined by the fluorine concentration in the cladding. With the POD process, numerical apertures in excess of 0.28 have been realized. In choosing the optimum NA for a certain application, considerations include the geometry of coupling light into and out of the fiber, as well as sensitivity to bend losses. If fibers undergo strong bending, the angle of total reflection can be exceeded by the light traveling in the fiber at the point of the strongest bending, see beam B in Figure 4. In order to minimize these losses a large NA (and/or a large CCDR) is required (Thyagarajan 1987).

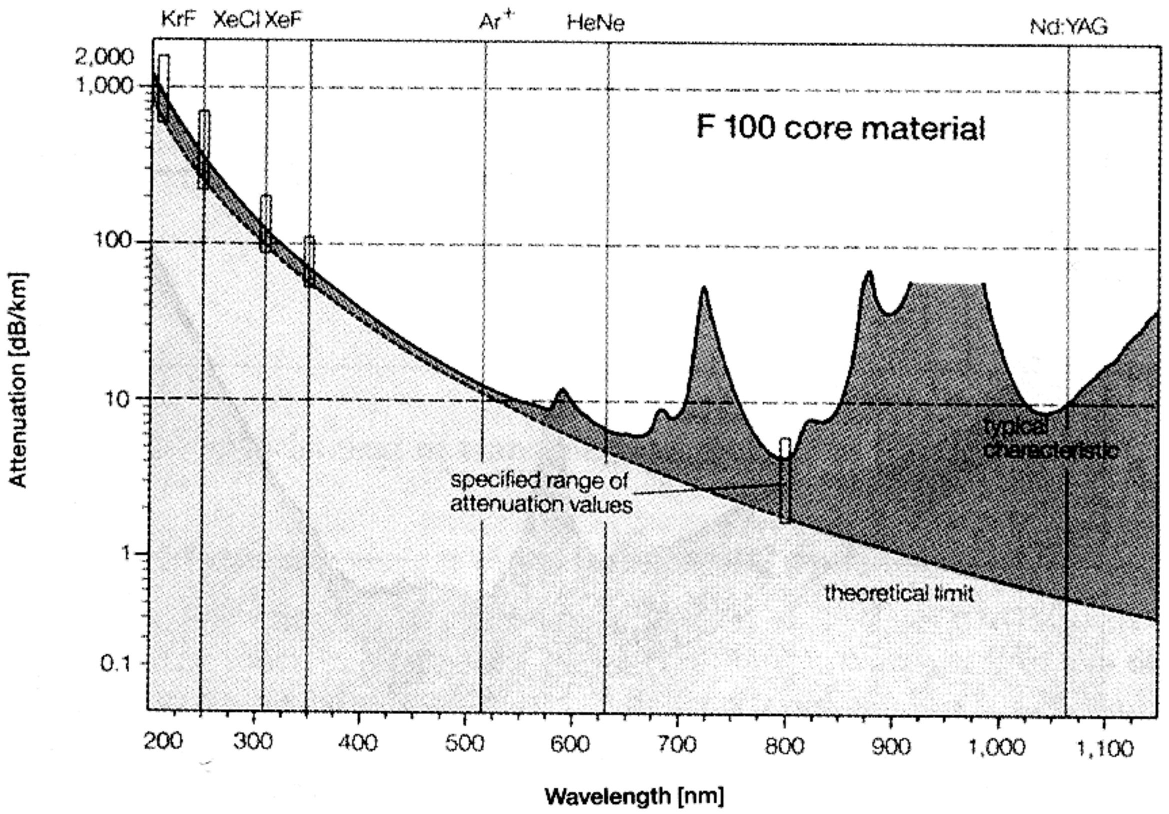

Figure 6. Typical attenuation of a Fluosil SSU fiber (OH content in the core around 700 ppm). The dashed line gives the theoretical limit of the attenuation in silica due to Rayleigh scattering.

Impurities Another reason for absorption bands in silica is the occurrence of impurities.

Metal impurities cause absorption bands, mainly in the UV and visible. The concentration of metal impurities is very low in state-of-the-art synthetic fused silica, so they have only a minor influence on fiber transmission.

The presence of bound hydroxyl (SiOH) in silica produces optical absorption bands due to the OH vibration (Humbach 1996). The fundamental resonance at 2722 nm has a very strong attenuation of 10 dB m^{-1} at an OH concentration of 1 ppm. Overtones of the fundamental mode and combined modes with the SiO_4 tetrahedron vibration show smaller but still significant absorption. The next bands in order of decreasing attenuation are located at 2212, 1383, 1246, 943, and 724 nm. These bands can be seen in the attenuation spectrum of a Fluosil SSU fiber (Fig. 6) having a silica core with an OH content of around 700 ppm.

Due to the production process, synthetic silica has a certain chlorine content, which is especially high in low-OH material. Chlorine can be found covalently bound to silicon (Si–Cl) as well as Cl_2 molecules in interstices in the glass matrix. According to Khalilov et al. (1994) there is no absorption band corresponding to the Si–Cl defect, but the interstitial Cl_2 causes a broad absorption band with a maximum around 320 nm.

4. Low-OH Fiber with Improved UV Transmission

As discussed in the last section, a fiber with high transmission in a broad spectral range (e.g. 350–1000 nm [2000 nm]) must have a low OH content, to avoid the strong vibrational absorption in the OH bands.

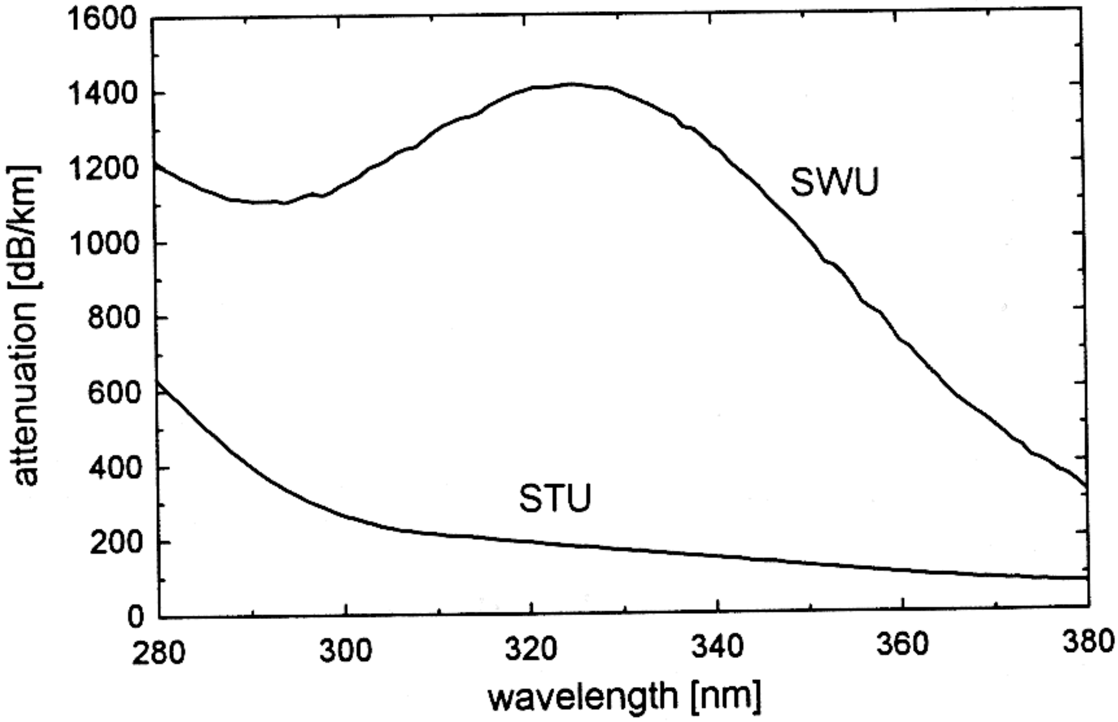

Figure 7. Attenuation of the standard low-OH Fluosil fiber SWU, and the recently developed STU in the region of the Cl_2 absorption band.

Unfortunately, low-OH materials have a much higher concentration of optically active intrinsic-defect centers than high-OH materials; this causes, depending on the type of silica, several absorption bands in the UV (see Table-1). In addition, low-OH materials usually have a higher chlorine content than high-OH materials.

In this paper we present the recently developed low-OH fiber Fluosil STU, which has an extended UV transmission range. This is achieved by using a core material with a reduced interstitial chlorine content avoiding the absorption band at 330 nm (see Fig. 7). The UV optical properties of this new core material do not show temporal changes, and hydrogen doping was not used for preform or fiber production. In Fig. 8 a) and b) the transmission after 10 m and 100 m of the STU fiber is compared with the transmission of standard low-OH and high-OH Fluosil fibers SWU and SSU.

The OH content in the STU preform is between 5 and 20 ppm, which causes higher OH absorption in the fiber compared to SWU, but the attenuation around 350 nm is much lower than in SWU fibers (Fig. 7). If low OH absorption is an important factor for the application, an STU-D preform is available with a similar core material as the STU but with an OH content less than 1 ppm (similar to SWU preforms). For this reason the IR transmission of STU-D is nearly the same as in SWU fibers, but the UV transmission is much better and

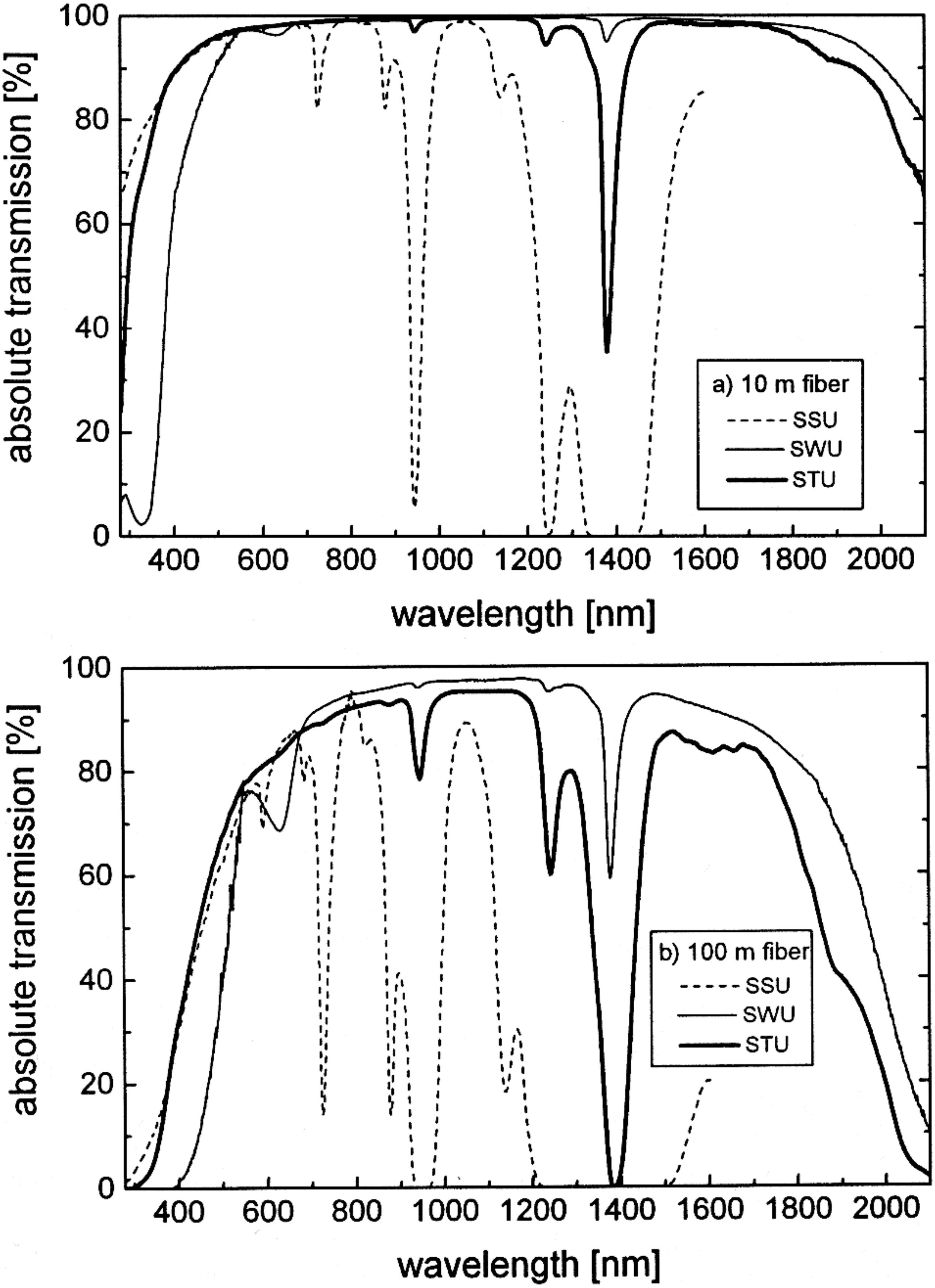

Figure 8. The transmission after 10 m (a) and 100 m (b) of the STU fiber compared with the transmission of standard low-OH fiber (SWU) and high-OH fiber (SSU).

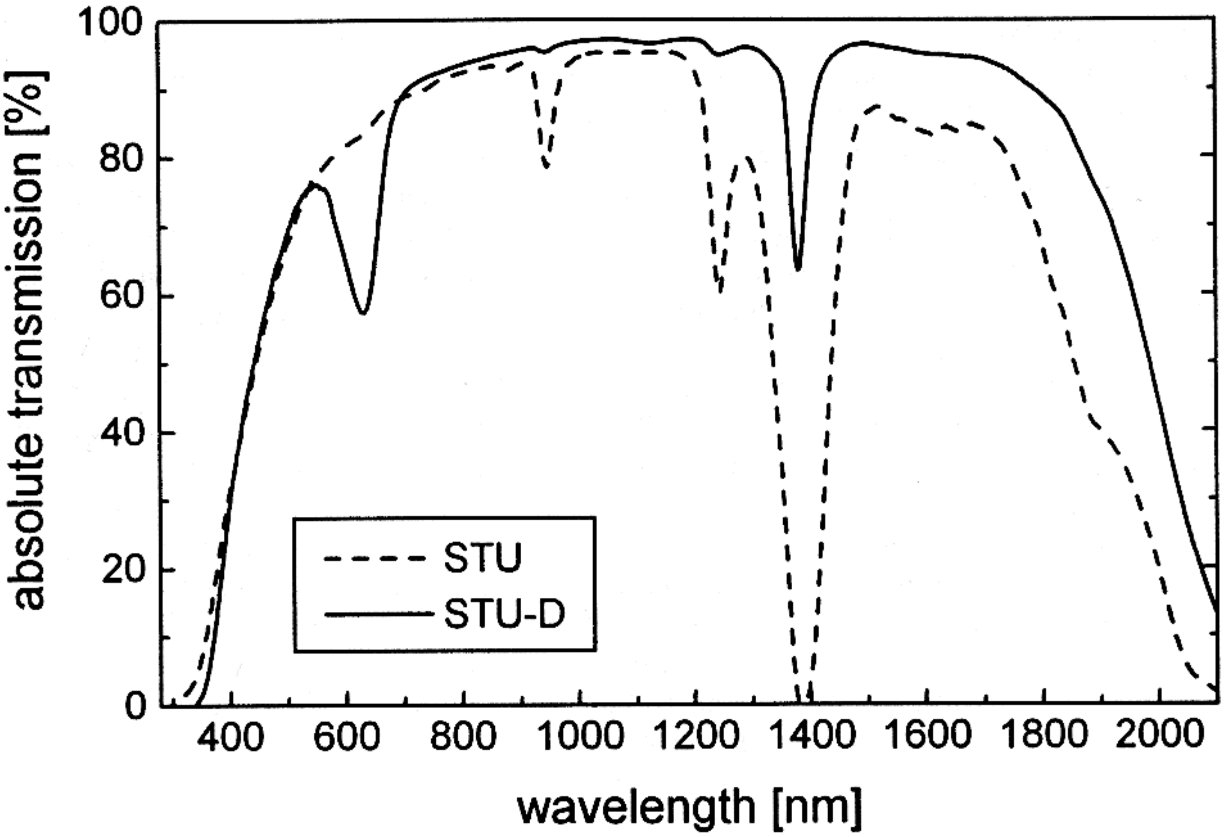

Figure 9. Transmission after 100 m of the STU fiber (5–20 ppm OH) compared with the transmission of STU-D fiber (1 ppm OH).

Table 2. Typical transmission and attenuation values of different fiber types

Wavelength (nm)	STU	STU-D	SWU	SSU
Transmission [%] after 10 m fiber				
300	54	29	6	71
350	79	66	6	85
400	91	87	71	91
450	94	93	81	94
500	97	97	91	97
Transmission [%] after 100 m fiber				
300	0.2	0.0	0.0	3.2
350	10.0	1.6	0.0	20.0
400	39.8	25.1	3.2	39.8
450	56.2	50.1	12.6	56.2
500	70.8	70.8	39.8	70.8
Attenuation in dB km^{-1}				
300	270	540	1200	150
350	100	180	1200	70
400	40	60	150	40
450	25	30	90	25
500	15	15	40	15

only slightly less than in STU fibers (see Fig. 9). The transmission after 10 m and 100 m, and the attenuation of the different fibers at certain wavelengths in the range 300–500 nm are given in Table 2.

Focal-ratio degradation (FRD) is a concern for most astronomical applications of optical fibers (Ramsey 1988). If FRD is significant in spectroscopic applications (that is, if the output beam from the fiber is faster than the input beam), a larger and more expensive spectrograph is required to maintain the same throughput, spectral coverage, and spectral resolution. Although there is no reason in principle to expect inferior FRD performance from STU fibers, careful FRD measurements were made at the Harvard–Smithsonian Center for Astrophysics, using a test setup similar to that shown in fig. 4 of Ramsey (1988). Production 25-m long polyimide-coated samples of 200-, 250-, and 300-μm core STU fibers demonstrated excellent performance when illuminated with an $f/6$ beam. Between 95 and 97% of the transmitted light (measured in an $f/3$ aperture) emerged in an $f/6$ beam. These numbers are very similar to those measured for fibers drawn from SWU and SSU preforms. The fibers were carefully mounted in v-grooves with a minimal amount of silica-filled epoxy and coiled in large diamter loops ($\sim$ 100- to 200-mm radius) for these measurements. Careless mounting and handling can easily degrade FRD preformance for any fiber.

5. Choosing the Optimal Fiber Type

SSU fibers offer excellent transmission, essentially without absorption bands in the wavelength range 190 to 550 nm. At longer wavelengths OH absorption bands (OH content is 600–800 ppm) limit the performance (Figs. 7–8).
SWU fibers contain core material with an OH content significantly below 1 ppm and have excellent transmission properties in the visible, near- and mid-IR spectral ranges, but at wavelengths shorter than 500 nm the transmission is lower than in SSU fibers.
STU fibers have a similar transmission spectrum to SWU fibers in the visible and IR with higher OH absorption bands due to the slightly higher OH content (between 5 and 20 ppm), but the transmission between 280 and 500 nm is much better than in SWU fibers. These fibers cover a very broad spectral range between 300 and 2100 nm, or even higher wavelengths if short fibers are sufficient for the application.
STU-D fibers should be chosen instead of STU if low OH absorption is important for the application. The OH content is less than 1 ppm and is therefore similar to SWU preforms. For this reason the IR transmission of STU-D is very similar to SWU, except the UV transmission which is much better than SWU and only slightly less than in STU.

6. Conclusions

Several factors affecting the optical properties of all-silica fibers have been discussed. Guiding losses in fibers can be minimized by the proper choice of CCDR and numerical aperture for each application. Transmission losses due to absorption in the core material have to be minimized by changing the core material. A new fiber with low OH content has been presented which has an extended transmission region in the UV combined with the excellent transmission of low-OH silica in the visible and IR. The improvement in the wavelength range 280–500 nm has been achieved by using a core material with reduced interstitial Cl_2 content. The UV (down to 280 nm) optical properties of this new core material are absolutely stable over time because hydrogen doping was not used in preform or fiber production.

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