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| Title: | Optical Fiber for UV-IR Broadband Spectroscopy | |
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| Date: | 1998 | |
| Source: | | |
| Publication: | Optical Astronomical Instrumentation | |
| Issue: | SPIE Vol. 3355 | |
| Page: | 884 - 891 | |

PROCEEDINGS OF SPIE REPRINT

SPIE—The International Society for Optical Engineering

*Reprinted from*

# *Optical Astronomical Instrumentation*

26–28 March 1998
Kona, Hawaii

Volume 3355

Box 10, Bellingham, Washington 98227 USA. Telephone 360/676-3290.

# Optical Fiber for UV-IR Broadband Spectroscopy

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## ABSTRACT

Optical fibers with broadband transmission from the UV through the IR have not been available because the silica core material either has OH absorption bands in the IR or UV absorption due to intrinsic structural defects or chlorine. We have developed a new silica core material which can be fabricated into an optical fiber with very good transmission characteristics from 350 nm to 2000 nm. The transmission performance is stable with time because the fiber is not doped with hydrogen.

**Keywords:** silica glass, optical fiber, broadband transmission, spectroscopy

## 1. INTRODUCTION

Spectroscopic data collection via fiber optics in telescopes requires an optical fiber with an unusually broadband transmission. Such a broadband, from the UV through the near-IR, has not been attainable even in all-silica optical fibers. This limitation is imposed by the properties of the core material which is usually undoped silica glass. Traditionally, such an undoped silica either has a high level of OH or a low level of OH. High OH silica has good transmission in the UV but the OH bands strongly limit transmission in the infrared. Low OH silica has good transmission in the infrared (upto 2000 nm) but structural and other defects cause a broadband increase in attenuation in the UV. Due to this limitation of the core material properties, spectroscopists have had to compromise on their ability to collect broadband information or have had to use two sets of optical fiber bundles, one optimized for UV collection and one optimized for IR collection.

We will briefly review fabrication methods and some of the optical properties of fibers which are important in specifying the optimum fiber for each application. We will then present the results for a new fiber type which has superior broadband transmission as well as minimal focal ratio degradation. This new fiber type has been made possible by a permanent change of the core material characteristics.

## 2. FABRICATION AND MEASUREMENT METHOD

Optical fibers are made by drawing a preform through a furnace; the diameter of the preform is typically reduced by a factor of several hundred times to the final fiber diameter. Single mode preforms used for long distance telecommunication fiber consist of a small central core of germania-doped silica surrounded by a large cladding of pure silica. However, such single mode fiber is not suitable for spectroscopy because the fiber has such a small core size and the transmission is optimized for the infrared only. Spectroscopic applications require the use of step-index, multimode fibers. The corresponding Heraeus Fluosil preforms are made by a proprietary Plasma Outside Deposition (POD) process. Rods of extremely pure synthetic silica glass, corresponding to the core, are coated with heavily fluorine-doped silica; the latter becomes the fiber cladding. The high temperature and non-equilibrium conditions of the plasma allow the incorporation of much higher levels of fluorine than in other fabrication methods such as used in telecommunication fiber production.

Focal ratio degradation was measured using test equipment was similar to that shown in Ramsey[1]. The fibers were carefully mounted in V-grooves with a small amount of silica-filled epoxy and coiled in large diameter loops (100 to 200 mm radius). Twenty five meter long polymide-coated fiber of 200, 250 and 300 micron core diameter were measured.

Part of the SPIE Conference on Optical Astronomical Instrumentation • Kona, Hawaii • March 1998
SPIE Vol. 3355 • 0277-786X/98/$10.00

## 3. OPTICAL PROPERTIES OF FIBERS

The optical performance of a fiber is controlled by a number of attributes including the optical transmission (which is principally determined by the core material), the cladding thickness and the numerical aperture. The effect of these characteristics will be examined in this section.

### 3.1 Numerical aperture

The numerical aperture NA is defined as:

$$NA = (n_1^2 - n_2^2)^{1/2} \qquad (1)$$

where $n_1$ is the refractive index of the core and $n_2$ is the refractive index of the clad. A typical numerical aperture for step-index, multimode fiber is 0.22, but can range between 0.12 and 0.28 in the case of fiber made from Fluosil preforms. A higher NA can be of benefit if the fiber is subjected to a small bend radius. Due to the change in geometry relating the incident light direction to the core-clad interface angle when the fiber is bent (see Figure 1), some of the light in the core is lost into the cladding. To minimize these losses, a larger radius of curvature, a higher NA and shorter wavelengths are desirable.

The numerical aperture also defines the maximum angle of incidence $\theta$ within which incident rays will be guided by the fiber.

$$NA = \sin\theta \qquad (2)$$

### 3.2 Cladding thickness

While in simple terms, light is confined to the core of the optical fiber by total internal reflection at the core-clad boundary, in reality, the situation is more complex. The electromagnetic fields in the fiber must meet the boundary conditions at the interface and consequently, fields exist in both the core and the cladding. The electromagnetic field in the cladding, or evanescent wave, can reach the outer diameter of the glass cladding if the cladding is too thin. This will result in excessive attenuation of the guided wave.

For a typical fiber with a numerical aperture of 0.22, the rule of thumb is that the cladding thickness should be at least ten times the longest wavelength of interest. If this condition is fulfilled, there will be no excess attenuation due to insufficient cladding thickness. However, it may be possible to use less than ten times the wavelength if the fiber length is short, e.g. a few meters. In such a case, the higher attenuation per meter is compensated by the short fiber length.

Preform and fiber geometry are frequently specified in terms of the cladding-to-core diameter ratio (CCDR) which is defined as the ratio of the cladding diameter to the core diameter. As an example, assume that the longest wavelength of interest is 1000 nm and the core diameter is 200 microns. The CCDR should be 1.1 because this will give a cladding thickness of 10 microns.

### 3.3 Intrinsic and extrinsic silica glass properties

The transmission of an optical fiber is determined primarily by the properties of the core material, although the cladding material can have an influence if loss mechanisms in the cladding material are sufficiently strong. For instance, in plastic clad silica (PCS) fiber, the plastic clad around the silica core has very strong absorption loss which leads to poor overall fiber transmission. Therefore, a silica glass cladding (with fluorine doping to achieve a lower refractive index than the pure silica core) is needed for high transmission.

Even if the core material is pure silica, the transmission will be lower than the theoretical limit due to intrinsic structural defects and impurities. When attenuation is plotted versus wavelength, the theoretical limit is a V-shaped curve with a minimum at 1550 nm. This is shown as the dashed curve in Figure 2. At shorter wavelengths, the minimum attenuation is

limited by Rayleigh scattering which is caused by frozen-in density fluctuations; Rayleigh scattering has a $\lambda^{-4}$ wavelength dependence. At wavelengths greater than 1550 nm, attenuation increases with wavelength due to phonon absorption.
In practice, intrinsic structural defects cause absorption bands, particularly in the UV. These defects[2] and the corresponding absorption bands are listed in Table 1. The exact conditions under which the silica glass is manufactured determines the stoichiometry of the silica and this in turn determines which of these structural defects are present.

Table 1 Intrinsic structural defects in silica glass

| **Name** | **Defect center** | **Absorption band** |
|---|---|---|
| E' | $O_3 \equiv Si^\bullet$ | 210/215 nm |
| *Oxygen rich silica:* | | |
| NBOH | $O_3 \equiv Si\text{-}O^\bullet$ | 630 nm |
| | $O_3 \equiv Si\text{-}O^-$ | 265 nm |
| peroxy radical | $O_3 \equiv Si\text{-}O\text{-}O^\bullet$ | 163 nm |
| peroxy linkage | $O_3 \equiv Si\text{-}O\text{-}O\text{-}Si \equiv O_3$ | 330 nm |
| *Oxygen-deficient silica:* | | |
| twofold coordinated Si | $O\text{-}{}_\bullet Si^\bullet\text{-}O$ | 247 nm |
| oxygen deficiency | $O_3 \equiv Si\text{-}Si \equiv O_3$ | 243 nm, 163 nm |

Impurities represent the extrinsic source of attenuation in silica glass. The principal impurities are OH, chlorine and metal ions. Bound hydroxyl (Si-OH) produces absorption bands at the following wavelengths, in decreasing order of strength[3]: 2722 nm, 2212 nm, 1383 nm, 1246 nm, 943 nm and 724 nm. The important effect of OH absorption is shown in Figure 3 which shows the attenuation of a Fluosil SSU fiber with about 700 ppm OH. It is clearly important to reduce the OH level if broadband transmission is needed. However, chlorine is used to remove OH in the production of low OH silica glass. Residual chlorine, typically 1500 ppm, causes a broad absorption band centered around 320 nm. Thus, there is usually a trade-off between having OH absorption bands in the IR and chlorine absorption in the UV. Finally, metal ions can cause absorption, particularly in the UV and visible wavelengths. However, metal impurities have been reduced to very low levels in state-of-the art synthetic silica glass, and these should not have a significant influence on fiber transmission.

## 4. IMPROVED BROADBAND TRANSMISSION FIBER

A temporary improvement in UV transmission can be obtained by hydrogen doping a dry fiber; this passivates some of the defects which cause UV absorption. However, the improvement is temporary because the hydrogen diffuses out of the glass. The goal of our work was to produce a dry fiber with intrinsically better UV transmission, i.e. without the use of hydrogen doping. This has been achieved by control of structural defect density and limiting the chlorine content of the glass. Preforms made with this new process have been designated as Fluosil STU.

The transmission of Fluosil STU fiber after 10 m and 100 m is shown in Figure 4a) and b); the transmission of standard low OH (Fluosil SWU) and high OH (Fluosil SSU) fibers is also shown. The strong improvement in UV transmission is shown in Figure 5. Fluosil STU has 5 to 20 ppm OH and this causes some absorption in the infrared, particularly at 1385 nm. If this is undesirable, a Fluosil STU preform with lower OH content is also available; this preform is designated as Fluosil STU-D and has less than 1 ppm OH (similar in OH level to Fluosil SWU). The transmission after 100 m of STU-D fiber is compared to regular STU fiber in Figure 6. Table 2 shows the transmission of the four preform types after 10 and 100 m as well as the attenuation in dB/km for wavelengths between 300 nm and 500 nm. Attenuation K in telecommunication fiber is usually measured in dB and is defined as:

$$K(dB) = 10 \log_{10} (I_0/I) \tag{3}$$

where $I_0$ is the incident intensity and I is the transmitted intensity. In addition to maintaining high transmission, it is also important to use fibers with minimal focal ratio degradation (FRD). Significant degradation of the output to input focal ratio will result in some combination of lower throughput, spectral coverage and spectral resolution. Fluosil STU preforms were drawn at Polymicro Technologies (Phoenix, AZ) and the focal ratio degradation was measured. After initial illumination with a f/6 beam, between 95% and 97% of the transmitted light (measured in a f/3 aperture) emerged in an f/6 beam. Thus, as expected, there is no difference in focal ratio degradation for STU compared to SWU or SSU fiber.

Table 2 Typical transmission and attenuation values of different fiber types

| **Wavelength** | **STU** | **STU-D** | **SWU** | **SSU** |
|---|---|---|---|---|
| **Transmission (%) after 10 m** | | | | |
| 300 nm | 54 | 29 | 6 | 71 |
| 350 nm | 79 | 66 | 6 | 85 |
| 400 nm | 91 | 87 | 71 | 91 |
| 450 nm | 94 | 93 | 81 | 94 |
| 500 nm | 97 | 97 | 91 | 97 |
| **Transmission (%) after 100 m** | | | | |
| 300 nm | 0 | 0 | 0 | 3 |
| 350 nm | 10 | 2 | 0 | 20 |
| 400 nm | 40 | 25 | 3 | 40 |
| 450 nm | 56 | 50 | 13 | 56 |
| 500 nm | 71 | 71 | 40 | 71 |
| **Attenuation (dB/km)** | | | | |
| 300 nm | 270 | 540 | 1200 | 150 |
| 350 nm | 100 | 180 | 1200 | 70 |
| 400 nm | 40 | 60 | 150 | 40 |
| 450 nm | 25 | 30 | 90 | 25 |
| 500 nm | 15 | 15 | 40 | 15 |

The characteristics of each of the fiber types discussed in this paper are summarized in Table 3.

Table 3 Fiber transmission characteristics

| **Fluosil preform type** | **Characteristics** |
|---|---|
| STU | Best for broadband transmission from 350 nm to 2000 nm with absorption peak at 1385 nm |
| STU-D | Similar to STU, but significantly lower absorption at 1385 nm and somewhat lower transmission below 400 nm |
| SSU | Best for deep UV transmission, but strong absorption bands above 700 nm |
| SWU | Best IR transmission but poor performance below 500 nm |

## 5. CONCLUSIONS

The wavelength dependence of optical fiber transmission is determined principally by the choice of the core material. In the past, the available choices of core material have led to compromises in broadband spectroscopy applications. Optical fibers were limited either in infrared transmission (due to OH absorption peaks) or in ultraviolet transmission (due to intrinsic structural defects and chlorine). These intrinsic and extrinsic defects were a necessary by-product of the manufacturing process.

We have shown that it is possible to manufacture a low OH silica core material which has a reduced level of UV absorbing defects. An optical fiber with broadband transmission from the UV through the IR is now commercially available without any compromise in focal ratio degradation or time stability of the transmission.

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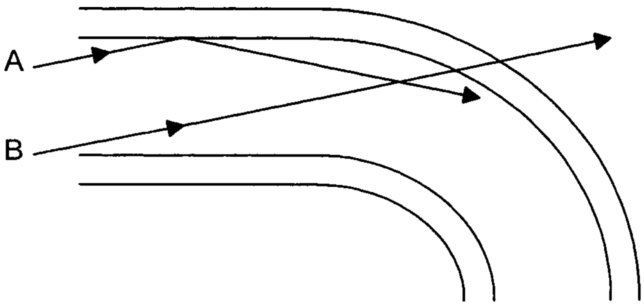

**Figure 1** Mechanism of transmission loss in bent fiber

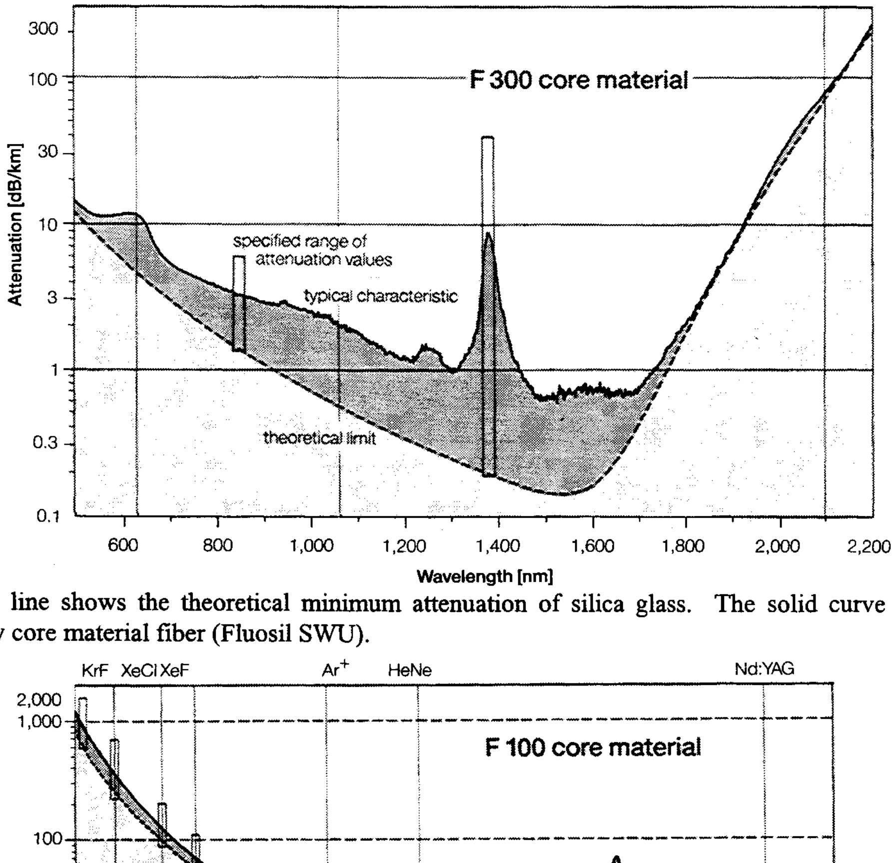

**Figure 2** Dashed line shows the theoretical minimum attenuation of silica glass. The solid curve shows the typical attenuation of a dry core material fiber (Fluosil SWU).

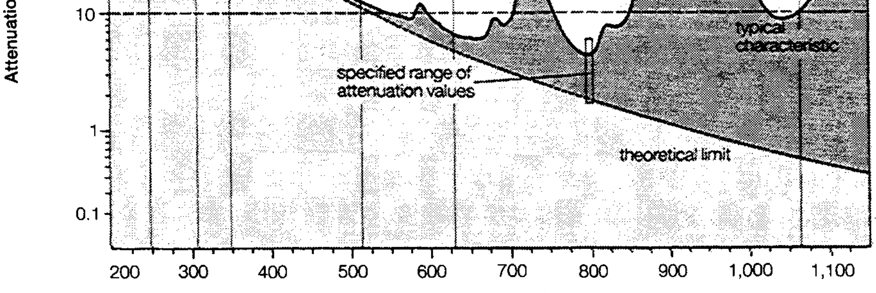

**Figure 3** Typical attenuation of a wet core material fiber (Fluosil SSU). Dashed curve shows the theoretical limit.

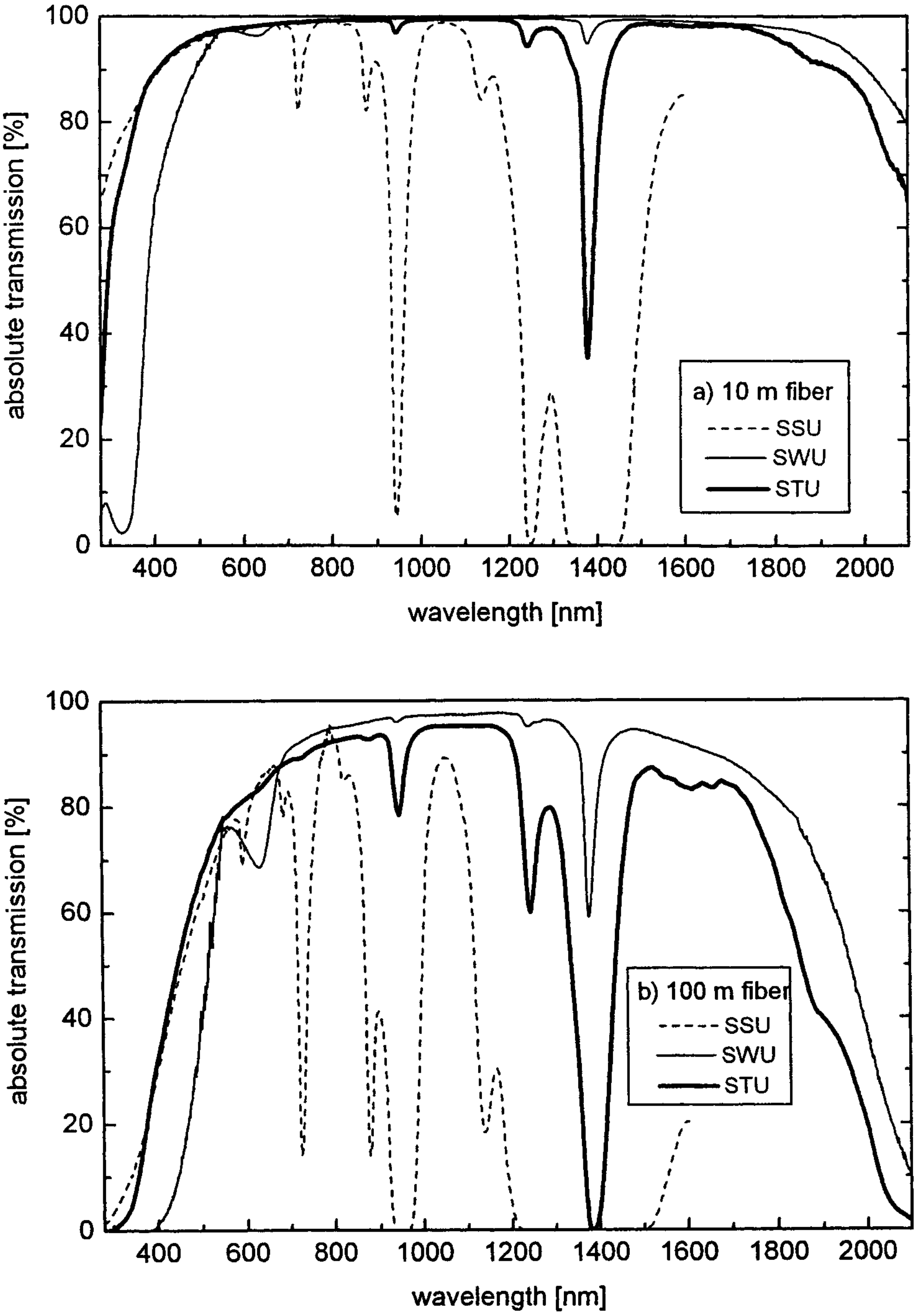

**Figure 4** The transmission after (a) 10 m and (b) 100 m of the STU broadband fiber compared with the transmission of standard low OH fiber (SWU) and high OH fiber (SSU)

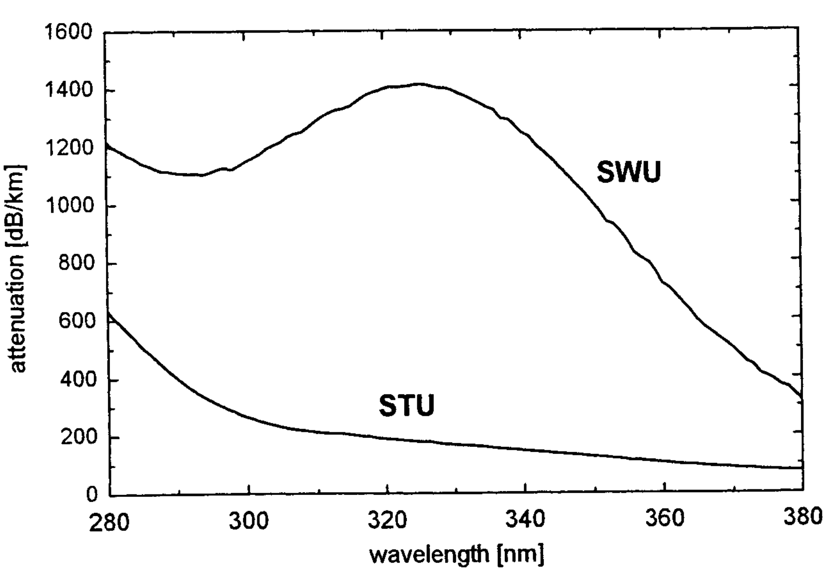

Figure 5 Comparison of the attenuation of STU fiber and standard low OH SWU fiber in the UV

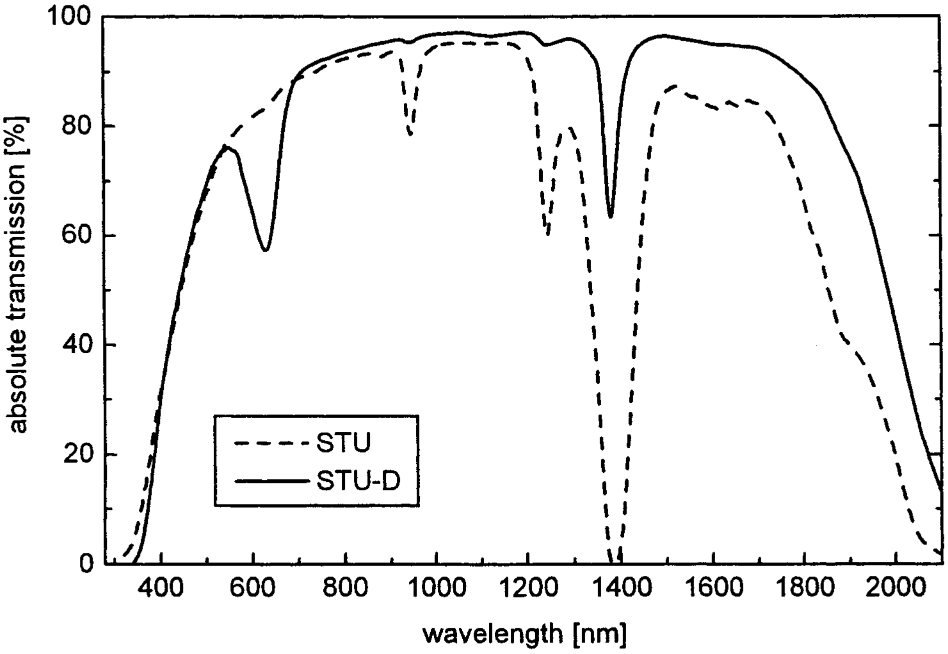

Figure 6 Transmission after 100 m of the STU fiber (5-20 ppm OH) compared with the transmission of STU-D fiber (1 ppm OH)