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Cladding Effects on Spectral Transmission of Optical Fibers for Medical Applications

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ABSTRACT

Key to many laser and sensor applications, in the medical area, is the desire to maintain high core to clad ratios for minimum penetration and maximum flexibility. The transmission of laser beams through optical fibers in a stable, uniform manner is a critical need and assumption for many surgical and sensing medical applications. Cladding thickness has been found to affect the transmission of signals across the electromagnetic spectrum in an uneven manner, especially when typical jacketing materials are used to protect the optical fibers against mechanical/environmental degradation. Experimental data and analysis of the effects of cladding thickness on the spectral transmission of optical fibers having core diameters below 300 µm are presented. Particularly for fibers with below 100 µm core diameters, fibers with cladding/core ratios below 1.2 are shown to have altered transmission spectra at wavelengths above 600 nm. The sensitivity is more pronounced for 'water-free', low-OH optical fibers, which have significant transmission through the near infrared [NIR] region.

1. INTRODUCTION

Medical applications require a range of geometries and clad-core ratios for step-index multimode fiber depending upon whether the end use is for laser surgery, illumination, or sensing. Fiber core geometries can range from 100µm to over 1000µm, and the clad-core ratios can range from 1.05 to over 1.20. In general, the smaller the clad-core ratio or the smaller the fiber core is, the less materials expense incurred and the more flexible the fiber is.

Commonly, laser surgery probe applications use fiber with a 1.1 clad-core ratio. However, when the core is thicker (500µm or greater), the clad-core ratio can be reduced below 1.1 without an increase in attenuation. Within the diode laser, however, eleven to nineteen smaller diameter fibers (under 200µm) are individually coupled to the diode emitters in the array and then they are bundled before being coupled into a single thicker delivery fiber. It is important and desirable to have the area of the bundled fiber as compact as possible to allow transferring the beam energy to the smallest diameter delivery fiber, in order to have the best control of power density at the treatment site.

In illumination applications, a bundle of smaller diameter fiber permits a more flexible endoscope for maneuvering within the body than thicker fiber(s). However, smaller diameter fiber has greater attenuation. A larger core size or a larger clad/core ratio will improve transmission but at a cost using extra space in the endoscopic instrument as well as increasing cost.

For sensing fibers, better sensitivity usually uses larger sensing area. In most medical applications, however the cross-sectional size needs to be small to permit flexibility and entry into small areas within a patient's body. Sensing through the side of the fiber can provide more area. In

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this case, thinner cladding may also be needed for adequate signal reception/generation and transfer into the core for transmission to the proximal detectors.

2. EXPERIMENTAL

The UV and VIS spectral losses of seven high-OH fibers were measured along with the NIR and VIS spectral losses of several low-OH fibers ranging in diameter from 100 μm to 320 μm. The "cutback" method was employed using a Monolight Optical Spectrum Analyzer (OSA), manufactured by Macam Photometric Ltd of Livington, Scotland. The system includes a scanning monochromator, a 3-channel controller, a power supply, two light sources (deuterium and tungsten), and input and output blocks to handle fiber from 70 μm to 1000 μm in diameter. A plastic tent was framed around the equipment table to prevent air disturbances from vibrating the fiber and affecting the measurements.

The "cutback" method consisted of using two pieces of same-type fiber with a length ratio of 1:4. For this study, the two fiber lengths were in the range of 50 m and 200 m. The longer lengths were measured via a Tektronics ODTR, and the shorter lengths were manually calculated (i.e. the number of loops were counted and multiplied by π times the diameter of the spool.) The "cutback" length (in meters) was obtained by subtracting the shorter length from the longer length of fiber.

The four fiber ends from the two spools of fiber were each prepared with a fresh cleave and inspected under a microscope for blemishes and re-cleaved if necessary. The ends were then dipped into acetone and air-dried for 15 seconds prior to insertion into the OSA.

The OSA input and output blocks have removable rubber and neoprene foam clamps for securing the fiber ends into a choice of six differently sized 90° V-Grooves. For this study, we opted to remove the clamps and used tape instead, as this was easier to handle the smaller diameter fibers. It was critical to position the input and output fiber ends exactly the same for each test. A 10X-magnified eyepiece helped to achieve this. Also, each spectral set of measurements was repeated twice to ensure reproducibility.

The test involved first inserting the two ends of the short length fiber into the input and output blocks to measure the signal and to make any gain adjustments. The short length fiber ends were marked "in" and "out" with tape, and the fiber was then carefully removed from the system without touching the cleaved end surfaces. Then the long length fiber was inserted into the same groove and position. Its signal was measured and had to be lower than the short length fiber for the test to proceed. In order to ensure the highest signal accuracy, the window of stability for the OSA was 15 minutes beginning with the capture of an acceptable signal from the long length fiber.

A tungsten light source was used for the VIS and NIR tests while a deuterium light source was used for the UV tests. The light was launched into the fiber via the over-fill, over-launch method. There was a block of pure silica between the light source and the input core/clad surface. The channel for the desired spectrum (UV, VIS, NIR) was selected, and the spectral analysis of the long length fiber was taken. The OSA took 400 averages over 30-40 seconds.

At the computer prompt, the long length fiber was removed and the short length fiber was exactly positioned as used in the previous signal acquisition. At the computer prompt, the cutback length (in meters) was entered. The OSA again took 400 averages, and the resulting spectral loss graph was displayed over the selected spectral range. The spectral loss graph was saved to the ASCII format and imported into Excel.

3. RESULTS

Figure 1 shows the typical spectral loss of high-OH fiber with glass core/clad geometries of 200/220μm and a clad-core ratio of 1.1 from the wavelengths 300nm to 1800nm. This spectrum was used as the standard for comparison purposes. Fiber having smaller and larger glass geometries and clad-core ratios were tested.

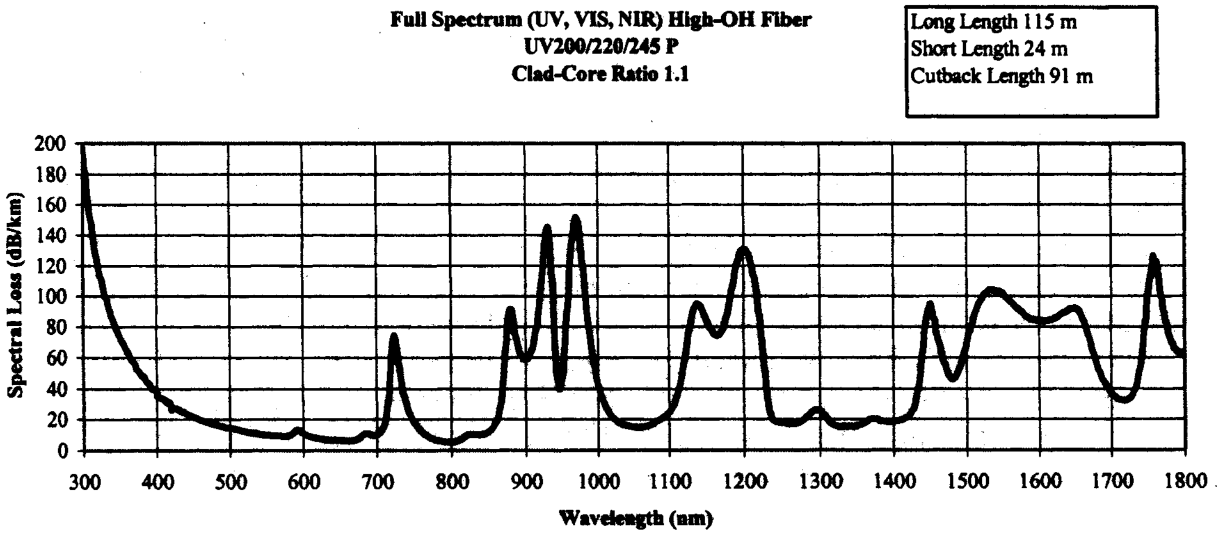
Full Spectrum (UV, VIS, NIR) High-OH Fiber
UV200/220/245 P
Clad-Core Ratio 1.1

Figure 1: Full spectrum (UV, VIS, NIR) high-OH fiber

Figure 2 shows the typical spectral loss of low-OH fiber with core/clad glass geometries of 200μm/220μm and a clad-core ratio of 1.1 from wavelengths 300nm to 1800nm. It was used as the standard for comparison purposes for the low-OH samples. Fiber having smaller and larger glass geometries and clad-core ratios were tested.

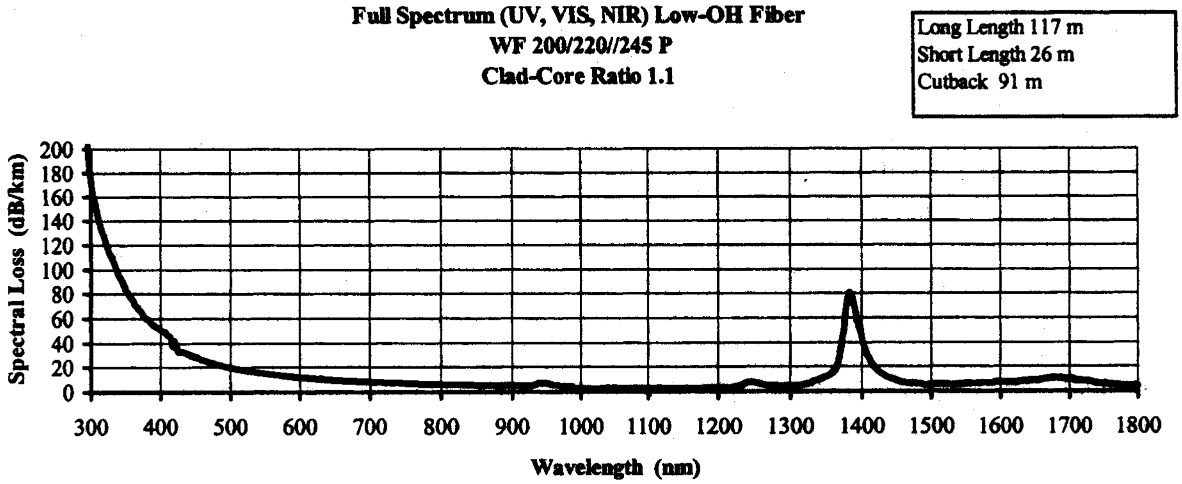
Full Spectrum (UV, VIS, NIR) Low-OH Fiber
WF 200/220//245 P
Clad-Core Ratio 1.1

Figure 2: Full spectrum (UV, VIS, NIR) low-OH fiber

For UV fibers despite differing glass geometries and clad-core ratios, the ultraviolet spectra were fairly consistent with one another. Representative samples are shown in Figure 3 for core sizes ranging from 80 μm to 200 μm and a clad/core ratio of 1.1. In Figure 4 are samples for clad/core ratios <1.1 and core sizes of ~ 200 μm.

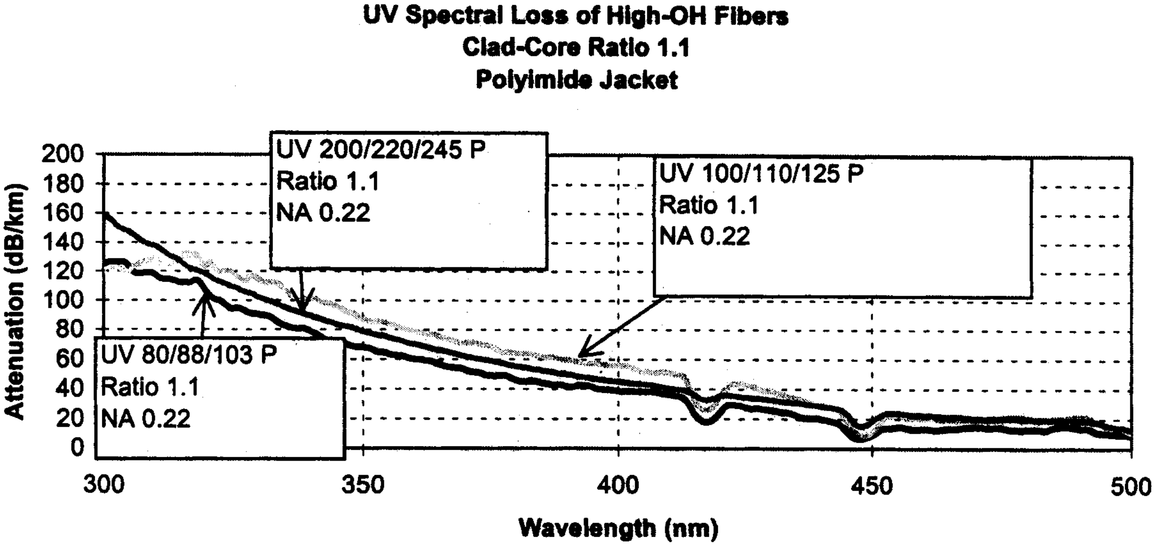

Figure 3: UV spectral loss of high-OH fibers with clad-core ratio of 1.1

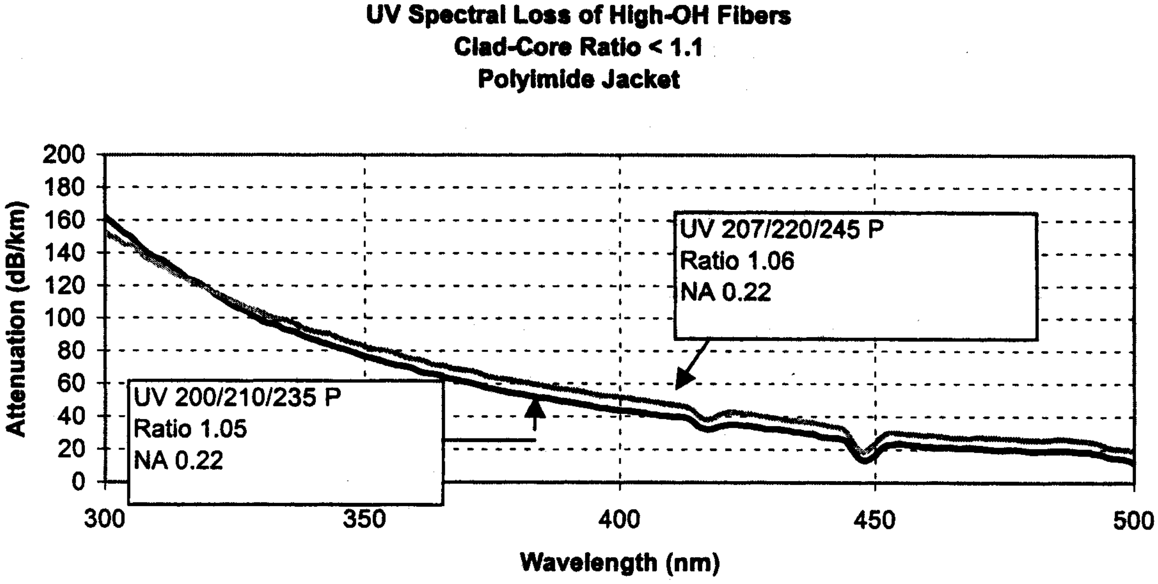

Figure 4: UV spectral loss of high-OH fibers with clad-core ratio < 1.1

Figure 5 shows the visible spectra of six high-OH fibers of various geometries and clad-core ratios. Only the 100μm/110μm fiber with the clad-core ratio of 1.1 showed an increase in attenuation between 750nm and 1100nm. However, once the clad-core ratio was increased to 1.2, the 100μm glass core fiber displayed no variation from the other spectra.

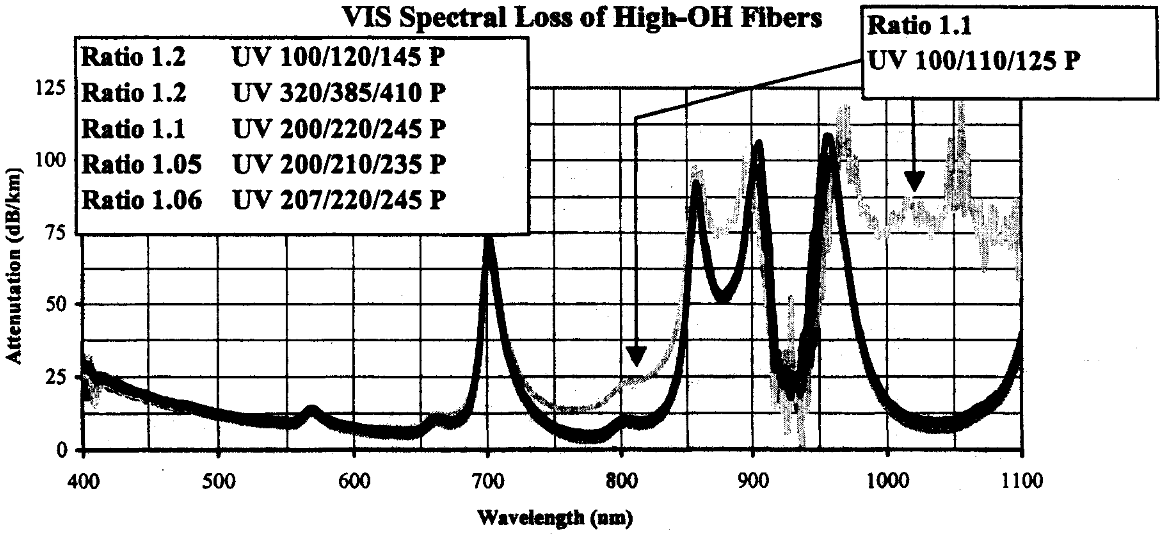

Figure 5: Visible spectra of six high-OH fibers of various dimensions

In contrast, Figure 6 shows the visible spectra of low-OH fiber with glass geometries of 200μm or less and clad-core ratios of 1.1. As the glass core is decreased below 200μm, the visible spectra begin to show greater attenuation at the higher wavelengths. For example, when the glass geometry is 120μm/132μm, the attenuation begins to increase at 800nm, and when the glass geometry is lowered to 100μm/110μm, the attenuation begins to increase at the lower wavelength of 600 nm.

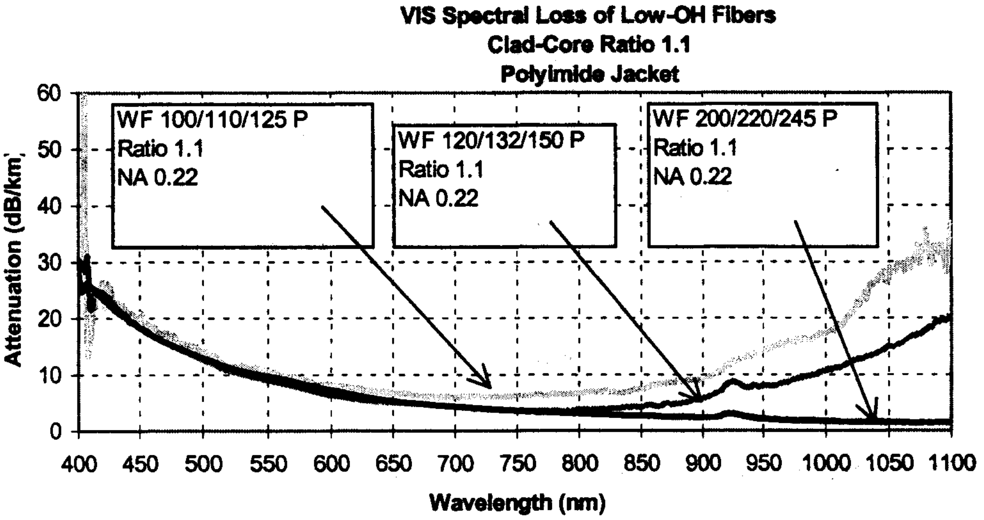

Figure 6: Visible spectral loss of low-OH fibers with clad-core ratio of 1.1

Figure 7 shows the NIR spectra for two of the fibers given in Figure 6. Note that for glass geometries below 200µm/220µm 100/110µm the NIR attenuation levels are increased in the wavelength range of 900nm to 1600nm for fiber with clad-core ratios of 1.1. Note also the qualitative difference, especially between about 1000 nm and 1500 nm for the fiber with the smaller core.

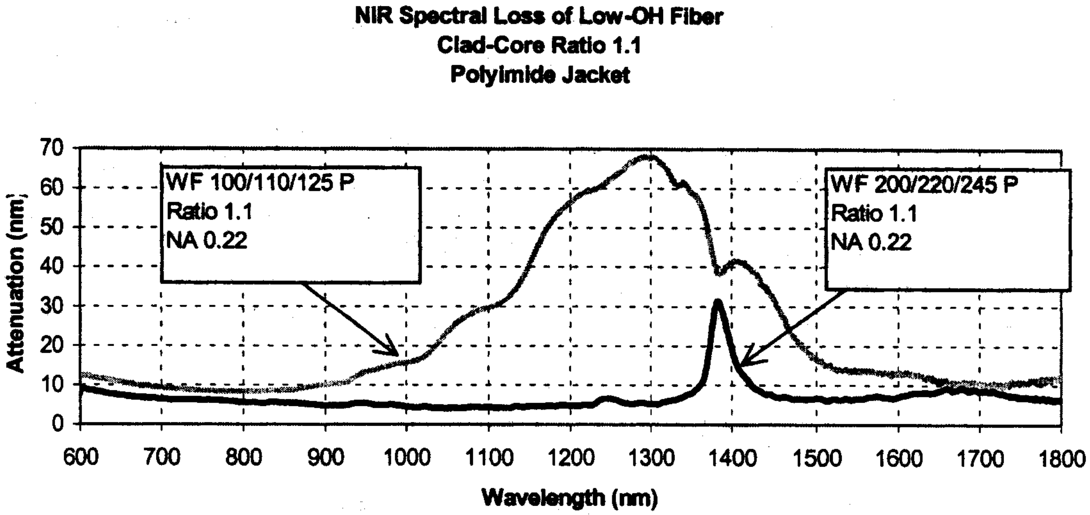

Figure 7: NIR spectral loss of low-OH fibers with clad-core ratio of 1.1

4. DISCUSSION

The effects on spectral transmission through an optical fiber by its clad/core ratio become important generally for low-OH fibers when the core diameter falls below 200 µm and the ratio is less than 1.2. For high-OH fibers effects become important below 150 µm cores diameters and when the ratio is less than or equal to 1.1.

Affects can occur in biomedical sensing creating the possibility of obtaining anomalous results. In laser surgical procedures, particularly with use of tapered fibers for delivery of broad band high intensity light, for example in hair removal applications, or of high power laser beams in the red or near infrared wavelength regions, intensity be lower than expected. Worse yet the intensity and the wavelength distribution may change with small shifts in source wavelength emission due to thermal or other effects during an extended procedure using near infrared lasers.

Even for illumination applications, where the use of high NA small, thin fibers is generally thought to be beneficial, care must be taken to ascertain affects due to clad dimensions below 10 µm. Furthermore, there are indications that higher NA fibers demonstrate larger effects arising in fibers having substantially equivalent core sizes and clad/core ratios.

Overall the effect is not merely to raise attenuation smoothly over all wavelengths, but rather wavelengths above 700 nm are generally affected first and to greater extents. The primary effect is to introduce spectral affects due to protective coatings over the cladding or in general introduce features of the environment beyond the cladding. Naturally, this effect could be beneficial, if the sensing application operates in the NIR region and, thus by choosing the right clad/core ratio and fiber size, the system would be more sensitive to changes in the environment.

Since the main affects begin appearing in the NIR region and then in the visible region of the spectrum, as noted in the previous section, it is understandable that the effects of small clad/core ratios are more important for low-OH optical fibers than for high-OH optical fibers.

In light of the above, the cause of the effects, described herein, logically seems to be related to the wave nature of the photons rather than their particle description, i.e. physical optics v. geometrical optics descriptions. As the core size drops below about 150-200 μm, more and more of the wave travels in the cladding as either the core size diminishes or the operating wavelength increases. The data clearly suggest that when the cladding thickness is approximately 10 or less times the wavelength being used or monitored, significant power is present at the cladding interface with the protective coatings or the outside environment. The spectral transmission of the optical fiber is, thus, significantly altered from that of pure or even lightly doped silica. There are probably several cases where this sensitivity can be used beneficially but in many other medical applications this will have to be considered further as the pursuit towards ever smaller core sizes proceeds with time.

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