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Fiber Coupling of Laser Diode Arrays for High Brightness: Cladding Considerations

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ABSTRACT

Diode laser arrays present challenges to delivering maximum brightness laser energy to remote sites. Coupling with optical fibers is key to achieving this goal. Fiber core diameters are chosen to capture all the energy from the slow axis, with fiber placement and/or lensing to assure capture output from the fast axis. Multiple fibers are then bundled as tightly as possible and their output focused into a single output fiber. The optimum brightness is achieved by using as small as possible bundle dimensions before reduction to the output fiber's dimensions. A major aim is thus to minimize jacketing and cladding thickness. Data and analysis of the effects of cladding thickness on the spectral transmission of optical fibers having core diameters between about 100 µm to about 300 µm are presented. Particularly below a 200 µm core, cladding thickness can significantly alter the transmission of laser energy in the visible and near infrared spectral regions, especially between 600 nm and 1700 nm. Data primarily deals with low-OH, 'water-free' fibers having cladding thicknesses between 5 to 20 µm. Especially for fibers having cladding/core ratios below 1.2, care must be taken to either use core sizes approaching 200 µm or work in the UV or lower visible wavelength region. Further guidelines are given below.

1. INTRODUCTION

Diode laser arrays present challenges to delivering maximum brightness laser energy to remote sites. Coupling with optical fibers is key to achieving this goal. Individual emitters within the diode array generally have a long dimension of about 100-150 µm and short dimension of about 2-4 µm. The divergence of the beam from the emitter is small along the long dimension, while it is much higher along the small dimension. The long dimension [axis] is thus called the slow axis and the small dimension [axis] is called the fast axis.

Fiber core diameters are usually chosen to capture all the energy from the slow axis, with fiber placement and/or lenses to assure capture of the output from the fast axis. The round cross section of the fibers already begins to diminish the brightness as the cross sectional area is much larger than that of the emitting diode. The number of coupling fibers is generally defined by the number of emitters in the diode array. The multiple fibers are then bundled as tightly as possible and their output focused into a single output fiber. Optimal brightness is obtained by being able to use as small a delivery fiber size as possible.

Besides power handling concerns, which are beyond the scope of this paper, the size of the delivery fiber is predicated on the size of the fiber bundle and the numerical apertures [NAs] of the diode coupling fibers, making up the bundle, and of the delivery fiber. There are material and practical limits to how large an NA is possible for the delivery fiber and likewise, physical and practical limits to how small an NA can =be used for the diode coupling fibers. The requirements of phase space approximately require that the NA of the delivery fiber be bigger than that of the

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coupling fibers by roughly the product of the reduction in size of the cross sectional areas from the fiber bundle to the delivery fiber.

Since coupling fiber dimensions and number are independently defined by the laser diode array structure, optimum brightness is, thus, achieved by keeping the bundle cross section as small as possible before the final reduction to the output fiber's dimensions, through appropriate optics. These considerations thus lead a desire to minimize jacketing and cladding thickness.

For lasers operating in the UV through blue-green regions of the visible spectral range, we shall see that only extreme pursuit of these goals may create problems. Beyond this we show below possible interference effects from jacketing and environment on the spectral transmission of optical fibers.

In another approach to transmission of high powered laser beams, attempts to increase beam brightness involve using a broad fiber cross section to gather high fluences of laser power and then tapering the fiber delivery system to raise the output brightness. Most laser applications use fiber with a 1.1 clad-core ratio. When the core is 400-500µm or greater, the clad-core ratio can be reduced below 1.1 without an increase in attenuation. However, if such a fiber is tapered down to 200 µm or below, the thickness of the cladding in the reduced cross section optical fiber and the environment at the cladding interface may cause problems as described below.

2. EXPERIMENTAL

The NIR and VIS spectral losses of sixteen low-OH fibers were measured along with the UV and VIS spectral losses of nine high-OH fibers ranging in diameter from 100 µm to 300 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 test 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 Tektronix 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 calculated 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 we found it easier to handle the smaller diameter fibers. It was critical to position the input and output fiber ends exactly the same for each test. We found a 10X-magnified eyepiece helped us to achieve this. Also, each test 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 core/clad surface. 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. (If it was not, the test was halted, and the long and short fibers were re-spooled, re-measured, and re-cleaved.) In order to ensure 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 glass 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 low-OH fiber with core/clad glass geometries of 200µm/220µm and a clad-core ratio of 1.1 from 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.

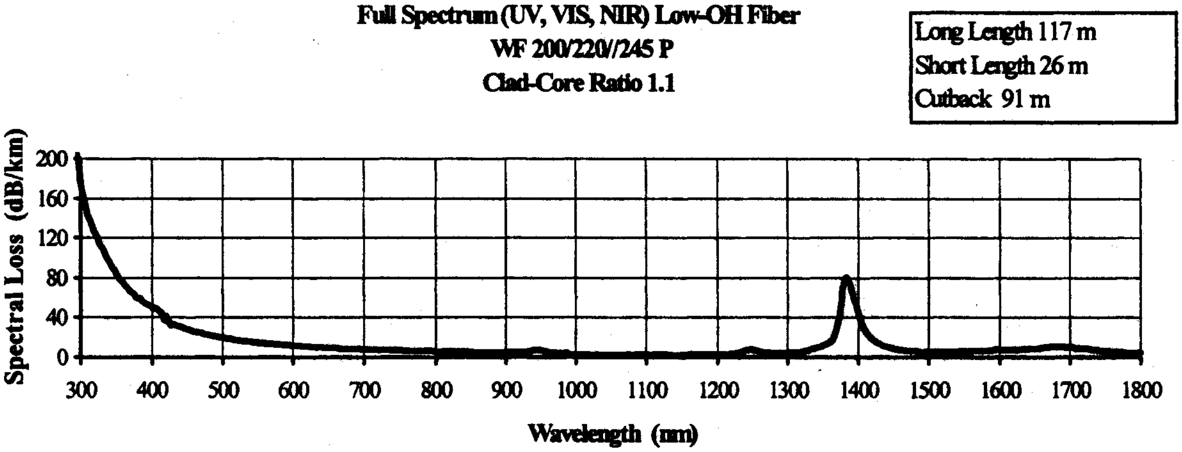

Figure 1: Full spectrum (UV, VIS, NIR) low-OH fiber

Figure 2 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 1100nm. It was used as the standard for comparison purposes for the high-OH samples. Fiber having smaller and larger glass geometries and clad-core ratios were tested.

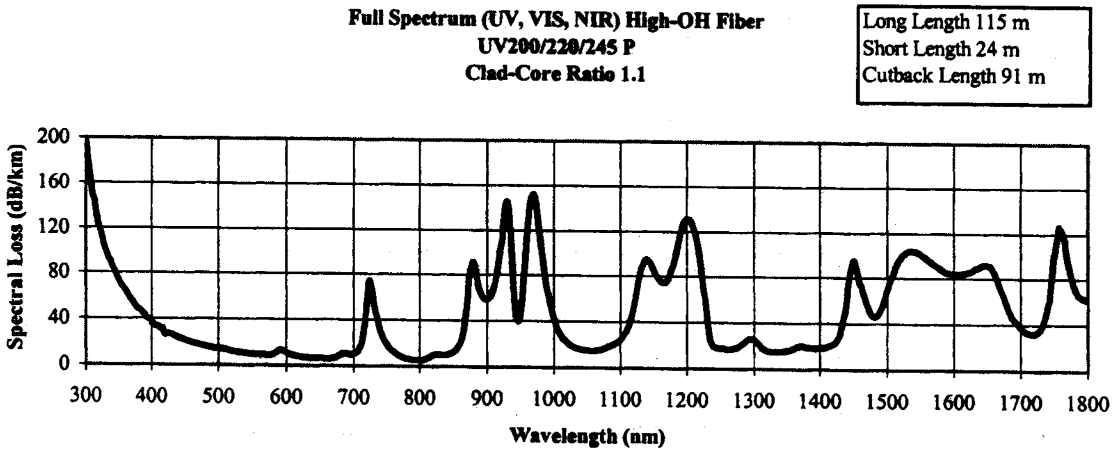

Figure 2: Full spectrum (UV, VIS, NIR) high-OH fiber

Figure 3 shows that fiber with clad-core ratios less than 1.1 and glass cores of 200µm or larger have consistent visible spectra.

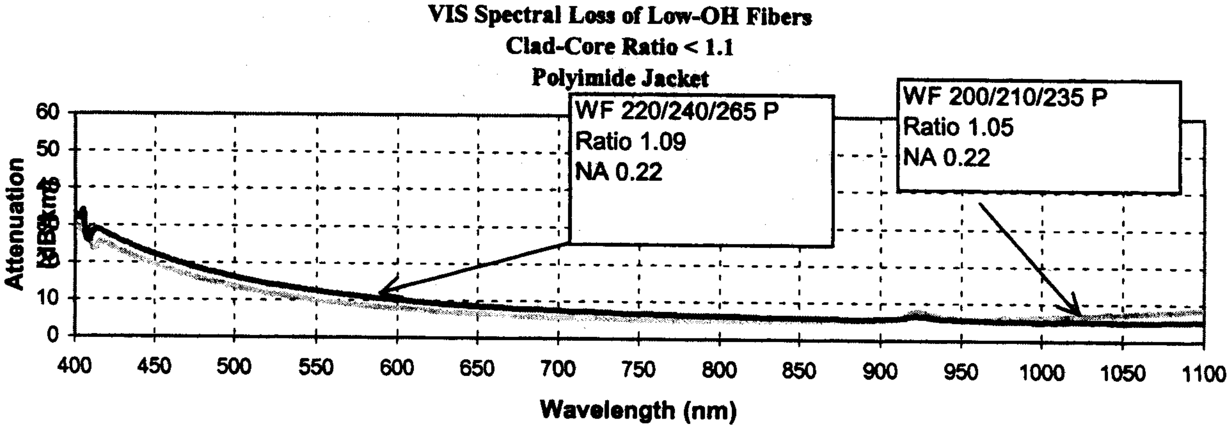

Figure 3: Visible spectral loss of low-OH fibers with clad-core ratios < 1.1

Figure 4 shows the visible spectra of 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.

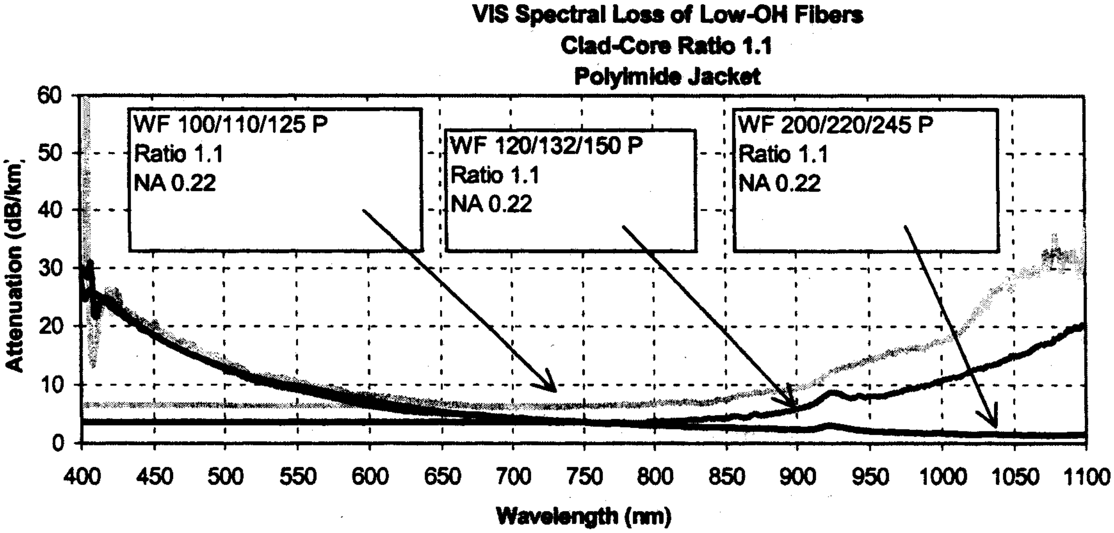

Figure 4: Visible spectral loss of low-OH fibers with clad-core ratio of 1.1

Figure 5 shows that as the clad-core ratio is slightly increased from 1.1 to 1.12, the glass core geometries can be decreased below 200µm to 160µm without greatly affecting the visible attenuation spectra. Decreasing the glass core geometry to 90 µm and 75µm causes the attenuation to increase exponentially at approximately the 775nm and 550nm wavelengths respectively.

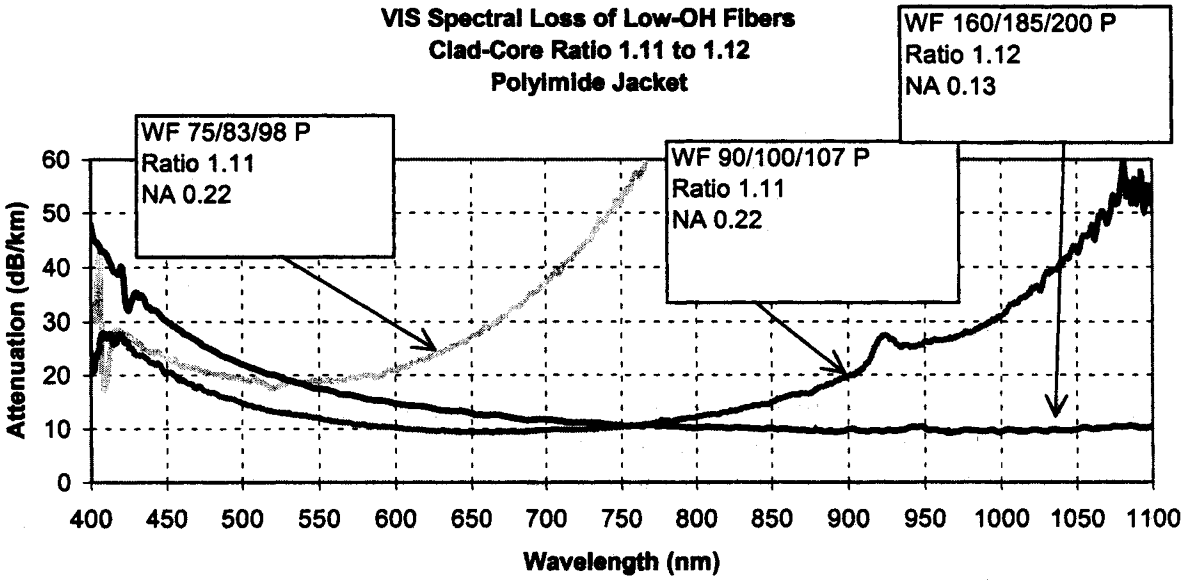

Figure 5: VIS spectral loss of low-OH fibers with clad-core ratios of 1.11/2

Figure 6 shows that by increasing the clad-core ratios to 1.2 or greater, the visible spectra remain fairly consistent with each other despite glass core geometries ranging from 84µm to 200µm.

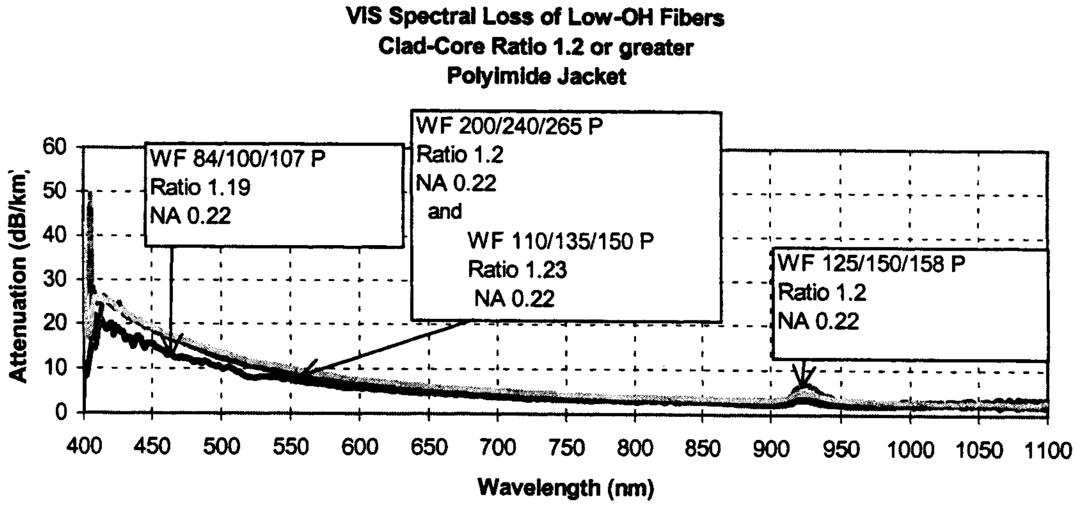

Figure 6: VIS spectral loss of low-OH fibers with clad-core ratios of 1.2 or greater

Continuing to use a fiber with glass core/clad geometries of 200µm/220µm and a clad-core ratio of 1.1 as the standard, the near infra-red spectra results are as follows.

Figure 7 shows that decreasing the clad/core ratio from 1.1 to 1.05 increases the attenuation levels in the higher NIR range beginning around 1200nm for fiber with glass geometries of 200µm/210µm.

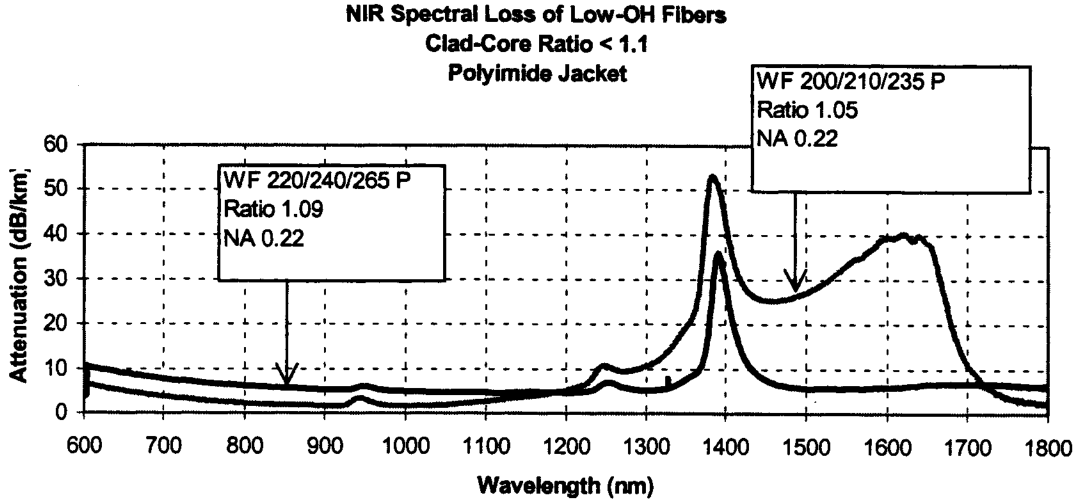

Figure 7: NIR spectral loss of low-OH fibers with clad-core ratio < 1.1

Figure 8 shows that decreasing the glass geometries from 200µm/220µm to 100/110µm increases the NIR attenuation levels in the wavelength range of 900nm to 1600nm for fiber with clad-core ratios of 1.1.

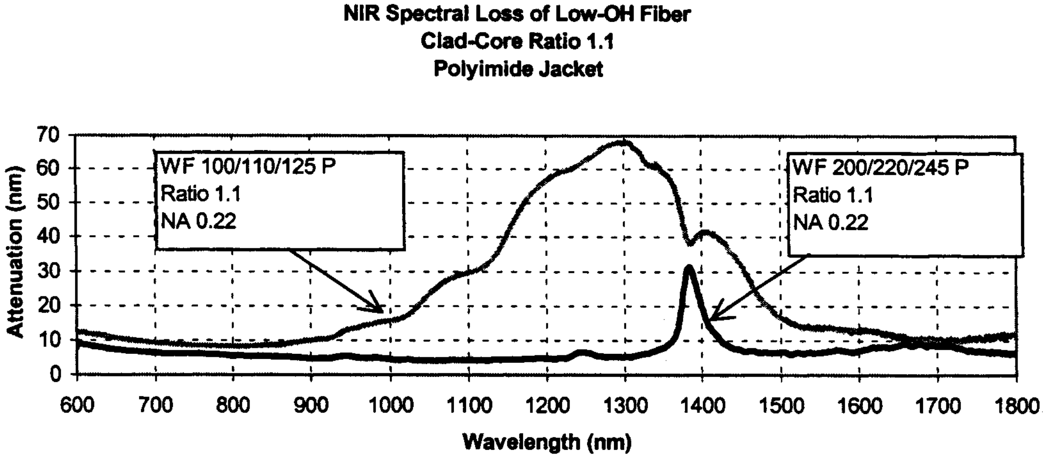

Figure 8: NIR spectral loss of low-OH fibers with clad-core ratio of 1.1

Figure 9 shows that by increasing the clad/core ratios to 1.2 or greater, the NIR spectra remain fairly consistent with each other regardless of glass geometries. Only the 84µm/100µm fiber showed an increase in attenuation at the 1450nm to 1800nm wavelength range.

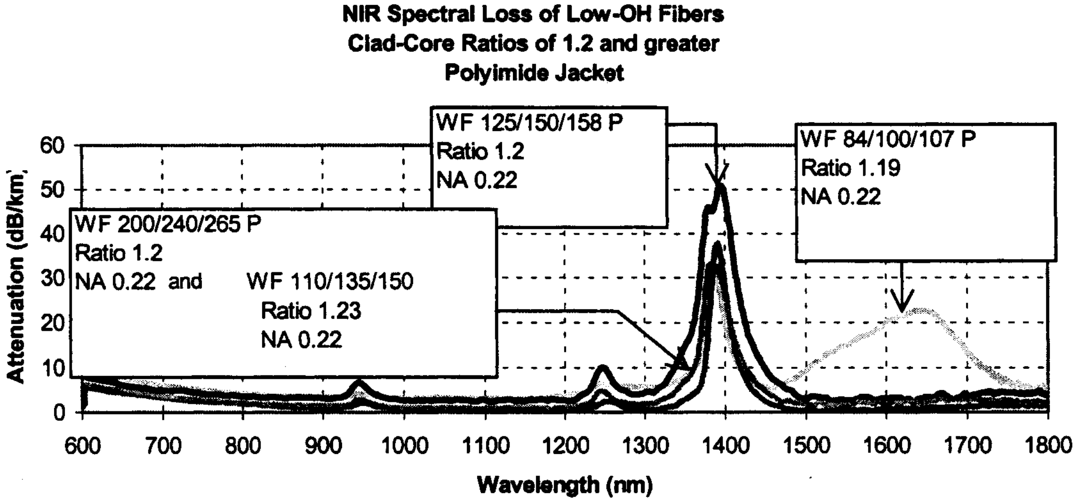

Figure 9: NIR spectral loss of low-OH fibers with clad-core ratios of 1.2 and greater

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.

Affects can occur in the coupling fibers as well as in the laser delivery fiber for a given diode array laser system. The concerns for coupling fibers are enhanced by the desire to keep the fiber core size as small as possible for the diode laser emitter used, and having as small as possible size for the bundle of fibers prior to direction into the delivery fiber. The latter demands the thinnest cladding and jacket dimensions, since the number of fibers and core size is minimally defined by the size and number of emitters per diode array bar. The concerns are allayed somewhat by using low numerical aperture [NA] for the coupling fibers, since there are indications that at lower NA the affects are smaller for a given core size or cladding thickness.

In any laser delivery system, creating tapered fibers can also bring these problems into play sooner than might be suspected. The tapering process can shift more power to the modes near the core/cladding interface. These higher order modes will be more greatly influenced by the cladding thickness as their wavefunctions are more extensive in the cladding. High NA values in the tapered region are not beneficial with reference to the effects described in this paper, although they may be favored for other reasons.

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.

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 applications this will have to be considered further as the pursuit towards ever smaller core sizes proceeds with time.

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