Improved Optical Fibers for Enhanced Coupling with High Power Diode Lasers

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ABSTRACT

A major problem with coupling high power diode lasers into optical fibers is the counter effects of requiring a synthetic silica core for its energy carrying capacity but needing also high numerical aperture and/or core size to capture the highly diverging fast axis light. Coupling the output of diode arrays efficiently and for maximum brightness retention involves additional problems, some of which are discussed. A possible solution to these problems is having the availability of higher numerical aperture [NA] fibers based primarily on a silica core and silica cladding. New deposition techniques have permitted the formation of preforms leading to fibers with pure silica cores which have an NA of 0.30 versus the standard 0.22 value. Further new structures and approaches to the problem have lead to optical fibers with a doped silica core having an NA above 0.50. Properties of these fibers are presented along with advantages they have for improving coupling high power diode lasers and also some newer concepts for improving retention of high brightness output from such laser systems.

1. INTRODUCTION

Diode lasers and diode laser arrays present challenges to delivering maximum laser energy power to remote sites. Coupling with optical fibers is key to achieving this goal. Individual emitters alone or within a diode array generally have a long dimension of about 100-150 µm and short dimension of about 1-4 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.

In an effort to capture all the power, 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. A previous paper dealt more with the special problems in maintaining brightness from diode laser arrays.[1] The cladding and core dimension effects on performance were mainly discussed in the context of maintaining high brightness. Here the power handling and enhanced capture of laser energy power is described in relation to the optical characteristics of a fiber, particularly its numerical aperture, NA. Further the sometimes conflicting restrictions, for maintaining high brightness and good coupling, on fiber dimensions and properties are considered in the discussion section below reflecting the benefits of the enhanced NA values for new fibers especially when used as delivery fibers.

For the highest power level handling/transmission over the broadest range of wavelengths the best optical fibers use a pure silica core and a doped silica cladding. This is especially true for high power, short wavelength laser sources, which do not generally fall in diode laser technology. In the past all silica fibers were restricted to numerical apertures of 0.22 or below. Early on pure silica core and doped silica clad fibers of this NA were not very thermally stable for large diameter sizes, e.g. much above 800 μm cores. The thermal problems were related to the interface between the doped and undoped silicas and over time were solved, so that today 0.22 NA fibers with cores much greater than 1 mm are available with suitable thermal stability. An NA of 0.22 has an acceptance angle of about 25 degrees. The fast axis divergence of most high power diode laser emitters is generally substantially greater than this. Capture in the fast axis dimension thus requires special considerations in the design of the total coupling optics package.

Optical fibers with enhanced numerical apertures are described below. Where and how optical fibers with differing NA and structures can be used to improve coupling to and transmission of high power laser diodes is discussed as well.

2. EXPERIMENTAL

The numerical apertures for the different fibers in this study were made using a set up which involved taking diameter measurements of the projections onto a black surface shielded from direct ambient light at five different distances from the fiber end. A white light source was over-launched and overfilled into the input end of the fiber. Meter long samples were used with about a 90 degree angle bend relative to the output end. The bend radius was on the order of a 40-50 cm. The ends were secured to metal blocks to guarantee stability of placement during testing and to improve reproducibility. NAs calculated at the five distances were averaged to yield the reported NA.

The NIR and VIS spectral losses of low-OH fibers were measured along with the UV and VIS spectral losses of high-OH fibers. The “cutback” method was employed using a Monolight Optical Spectrum Analyzer (OSA), manufactured by Macam Photometric Ltd of Livingston, 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 about 1:4. For this study, the two fiber lengths were in the range of 20-50 m and 60-200 m. The longer lengths were measured via a Tektronix OTDR, 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. (UV eye protection was worn). 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 numerical aperture (NA) of 0.22 from the wavelengths 300 nm to 1800 nm. This fiber has pure undoped silica as the core material and Fluorine-doped silica as the cladding.

Figure 2 shows the typical spectral loss of high-OH fiber with core/clad glass geometries of 200µm/220µm and a numerical aperture (NA) of 0.22 from the wavelengths 300 nm to 1500 nm. This fiber has pure undoped silica as the core material and Fluorine-doped silica as the cladding.

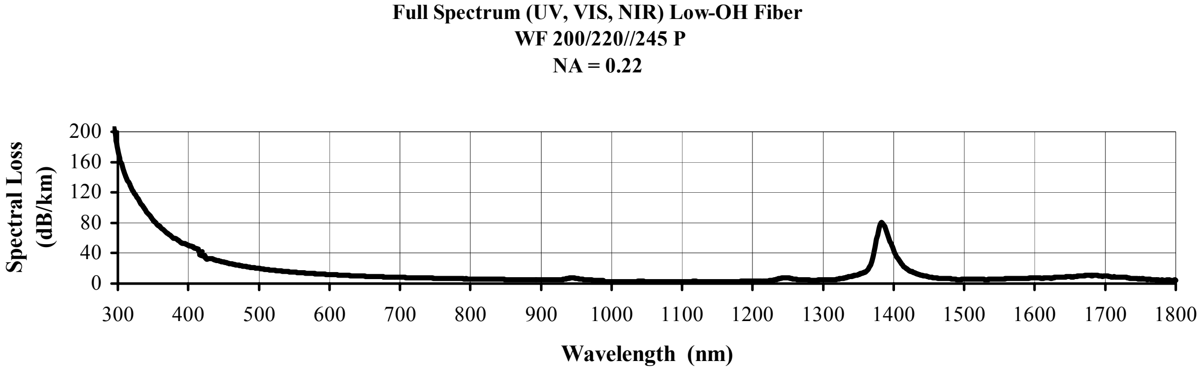

Figure 1: Full spectrum (UV, VIS, NIR) low-OH fiber

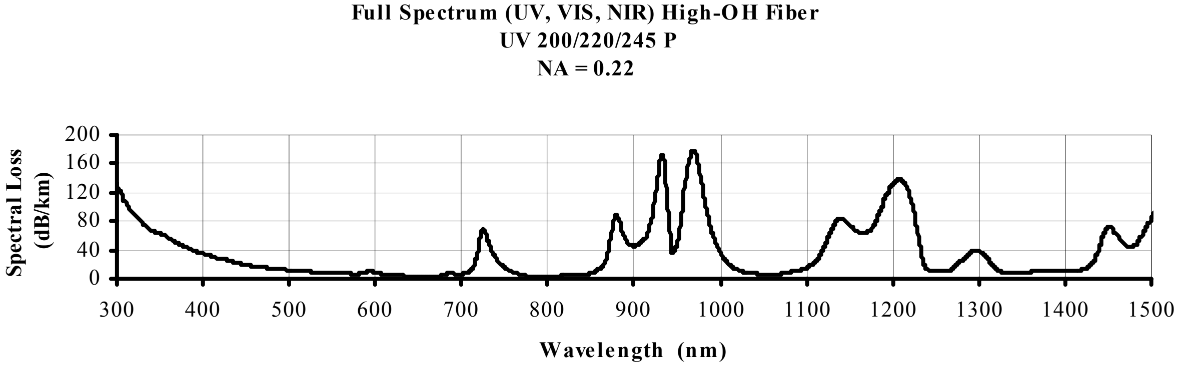

Figure 2: Full spectrum (UV, VIS, NIR) high-OH fiber

Figure 3 shows the ultraviolet, visible and near infrared spectral loss for a high-OH fiber with an NA of 0.30. Again qualitatively the spectral loss is substantially similar to that of the standard NA optical fiber of Figure 2. Although OH associated peaks are smaller than for the previous sample, they are still somewhat higher those measured for the standard undoped all silica fiber.

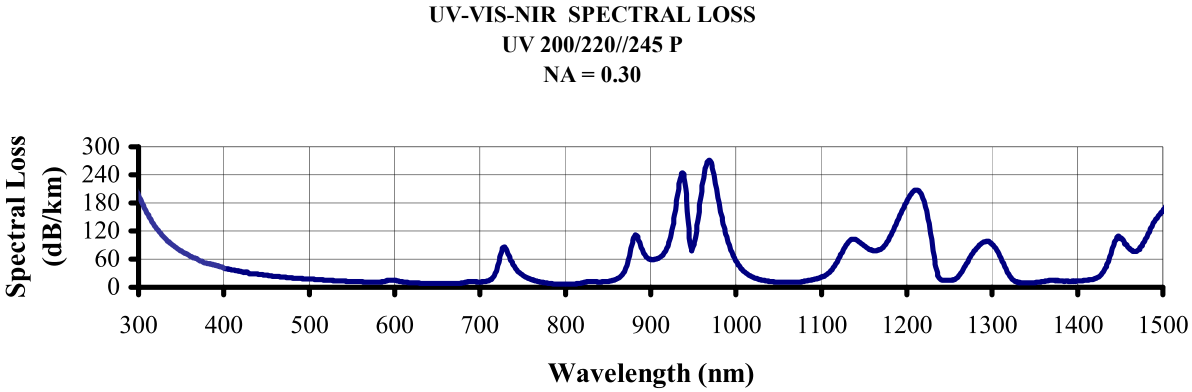

Figure 3: Ultraviolet, visible, near infrared spectral loss of 0.30 NA high-OH fiber

For the undoped all silica fibers, larger than standard NA fibers have also been made with low-OH fibers. Sample spectral loss for a low-OH fiber having an NA of 0.30 is shown in Figure 4 for the visible and near infrared regions of the spectrum. This spectral loss can be compared to that of the standard NA low-OH fiber shown in Figure 1. The spectral loss is essentially the same, with this sample having a slightly higher OH level, though still <1 ppm.

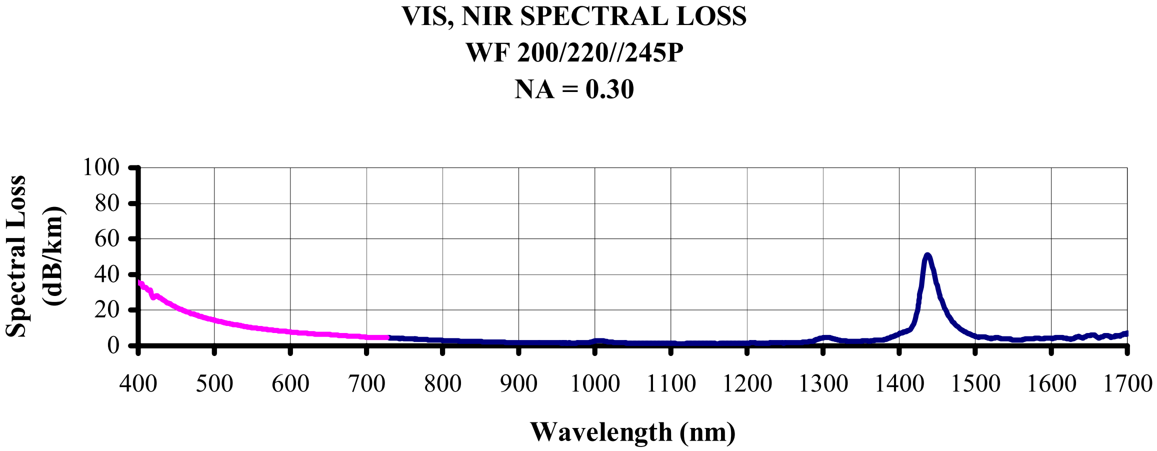

Figure 4: Visible, near infrared spectral loss of 0.30 NA low-OH fiber

Figure 5 shows the spectral loss for a low-OH fiber where the core material is now a Germanium-doped silica and the clad material is Fluorine-doped silica. This is the Optran Ultra^2 fiber with an NA of 0.37. Note that the OH level for these fibers is about 1/5 that of the standard fiber represented n Figure 1.

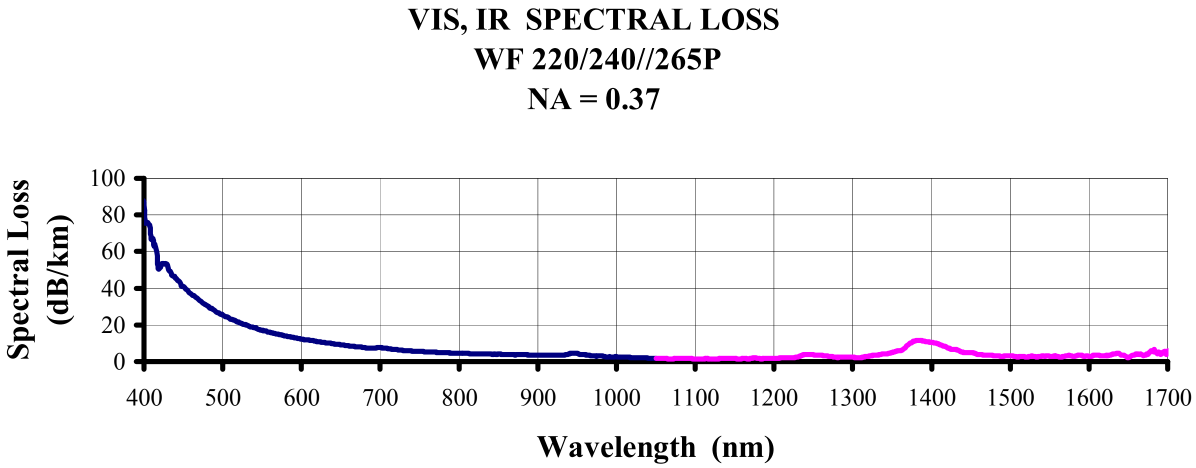

Figure 5: Visible, near infrared spectral loss for 0.37 NA low-OH fiber

Figure 6 shows the visible and near infrared spectral loss for fiber with NA value of 0.56. The spectral loss behavior is essentially similar to the fiber measured in Figure 5. Both have Ge-doped silica cores and F-doped silica claddings. Here the OH level is about the same or lower than the NA 0.37 sample in the previous figure.

Overall the spectra shown indicate that both the high NA pure silica core fibers and the high NA germanium-doped silica core fibers have spectral responses essentially similar to those for the standard fiber products having the same chemical materials.

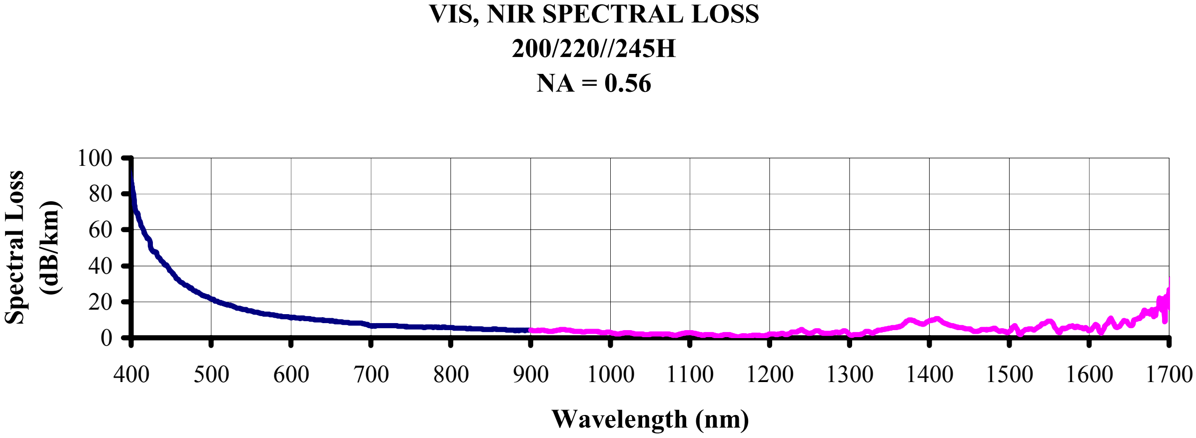

Figure 6: Visible, near infrared spectral loss for 0.56 NA low-OH fiber

Figure 7 presents a comparison of the acceptance volume/surface for optical fibers having the same core dimension and varying numerical apertures (NA) as indicated for each shape; standard silica/fluorosilica fibers at 0.22, and a newest silica/fluorosilica fiber at 0.30.

Note that the surface area of the acceptance circle, at a fixed distance from the fiber end grows very dramatically as one goes from the fiber with the lowest NA to one with the highest NA. Setting the NA = 0.22 fiber arbitrarily at 1, the NA = 0.30 fiber has an acceptance circular surface, which is 80% larger. For the germanium-doped silica fibers, the NA = 0.37 fiber has an acceptance circular surface, which is 183% larger, and the NA= 0.56 fiber has an acceptance circular surface, which is 550% larger. This dramatic increase demonstrates the improvement in coupling possible under the proper circumstances.

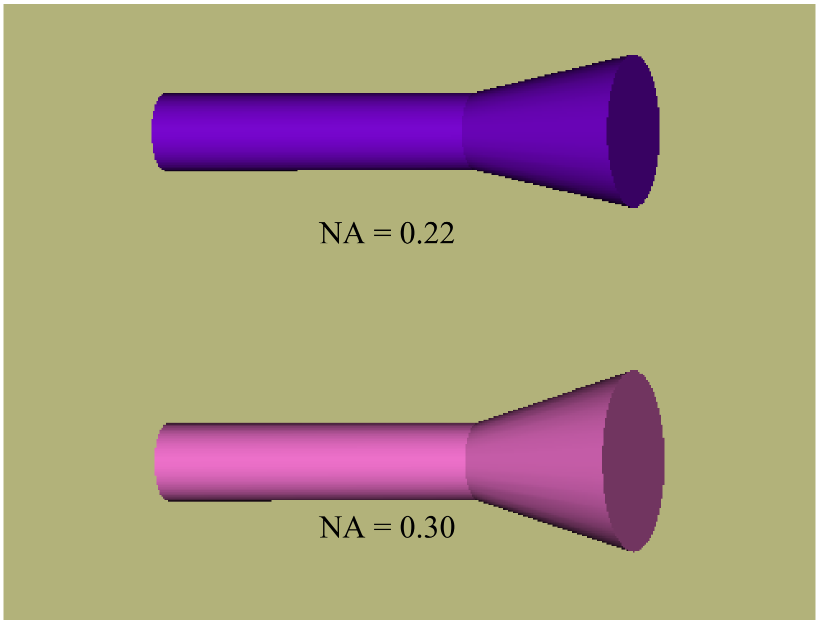

Figure 7: Schematic representation of the Numerical Aperture of selected optical fibers

4. DISCUSSION

For most high power diode laser systems, a diode array of individual emitters or one or more multi-emitter bars are used. Typically each emitter is coupled to an individual optical fiber. The coupling fibers are then grouped together and through some optics module projected onto a delivery fiber. 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. The requirements of phase space approximately require that the NA of the delivery fiber be bigger than that of the coupling fibers by roughly the product of the reduction in size of the cross sectional areas from the fiber bundle to the delivery fiber.

The dimensions and divergence of the diode laser emitters define the core size for the coupling fibers. Prior work[1] on cladding/core ratios and core sizes have placed restrictions on minimizing the ratio for the core sizes usually defined by the emitter dimensions. The smaller the dimension of the delivery fiber the more flexible and the higher the fluence that can be projected onto a treatment site from the distal end of the fiber. The higher the NA of the delivery fiber, the greater can be the reduction in spot size from the fiber bundle to the delivery fiber core size. Alternatively, the larger the NA of the delivery fiber, the larger the NA of the diode coupling fibers for a given delivery fiber core size or number of fibers within the bundle. In the extremes, this is where the highest NA fiber, NA = 0.56, would have the most value.

Internally, one might argue that the use of a fiber with an acceptance angle nearly equal to the fast axis of the diode laser emitter for coupling, could lead to a more compact and reliable package by removing the need for extra optics between the emitter and the coupling fiber. Early on the fast axis divergence for high power individual emitters was over 40 degrees. Recent advances in diode laser emitters has improved beam quality so that the fast axis beam divergence is less than 35 degrees. The new pure silica core fiber with an NA of 0.30 have an acceptance angle of 35 degrees. Even the new fibers with an NA of 0.28 has an acceptance angle of 32.5 degrees, making it nearly a match as well. In the future, using flat surfaced [3] coupling fibers with such high NA values will permit creating a much smaller dimensioned bundle, which then could be reduced in half to a delivery fiber having an NA of 0.56 to provide an uncommonly high power density at the distal end of the delivery fiber.

In conclusion, it should be added that many of the comments brought forth here are also important where the light sources are high performance light emitting diodes, super luminescent diodes and the like.

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1. B. J. Skutnik and H. Park, "Fiber Coupling of Laser Diode Arrays for High Brightness: Cladding Considerations", SPIE Proc. **4629**, 86 (2002).
2. Optran Ultra is a trademark of CeramOptec Industries/Biolitec.
3. US Patent # 5,566,267, issued 10/15/96; by Wolfgang Neuberger, assigned to CeramOptec Industries, Inc.