Optical Fibers for Improved Low Loss Coupling of Optical Components

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ABSTRACT

An important feature of achieving low coupling losses in systems with small dimensions is the availability of optical fibers with larger numerical apertures while retaining the excellent loss characteristics of synthetic silica. Larger acceptance angles permit more efficient pick up of signals in smaller diameter optical fibers. Likewise broader angles can benefit illumination systems, providing larger areas of coverage with smaller components. Examples where one or both aspects are valuable include remote spectroscopic sampling and hands-free fiber optic illumination systems for hazardous environments. Optical fibers with doped synthetic silica cores are described which have numerical apertures of over 0.50 for power delivery and effective NAs approaching 0.60 for illumination, sensing or other 'low power' applications. Spectral and optical properties of these fibers are presented along with how they allow improved low loss coupling of optical components in photonic and microelectronic systems.

1. INTRODUCTION

Laser based applications in micro-packaging, microelectronics, and optoelectronic manufacturing benefit from the use of optical fibers coupled to the laser sources. Both economical and technical benefits are possible. Efficient coupling is key to accepting laser beam energy into the fibers for many cases. In some cases the ability to spread the output may be the key factor. Efficient coupling can also be critical in remote spectroscopic sensing. A relatively uniform output over a broad area is especially valuable when illumination of a tight area is required. Hands free illumination, where a modest area of view is needed, is another area where a broader output from a smaller fiber would be very helpful. In both types of cases the availability of optical fibers having low optical losses and high numerical apertures provide the opportunity to use smaller dimensioned fibers while still maintaining highly efficient coupling. Smaller fibers are more flexible, more resistant to fatigue, occupy less space and weigh less.

Classically, using laser energy for other than communications, data transfer, or sensing usually involves lasers with moderate to high output power, as in laser welding, marking or ablation. Transmission of such laser energy requires a medium with high temperature stability and ultra low loss, so that the heat gain from internal absorption and its effects are minimized.

Silica is a good material in terms of both its optical and thermal properties. It can be produced synthetically with ultra-high purity and it has little absorption across a wide range of wavelengths from about 200 nm to over 2000 nm, especially when its production processing includes minimization of OH bonds within the glassy silica structure. The glassy region for silica is thermally stable to well above 1500 C. The bond energy of silica is greater than 20 GW/cm^2. Silica core/clad fibers are thus among the best materials to use in optical fibers for high energy laser transmission.

The transmission and/or thermal properties of silica are generally reduced by any significant doping of the material to change its refractive index. Among the problems that arise is that the thermal expansion coefficient of pure silica is very small, whereas doped silicas usually have higher thermal expansion coefficients. Until very recently this was a major problem limiting the ability to manufacture thermally stable silica/silica(F) core/clad fibers to a Numerical Aperture (NA) of no greater than 0.22. Doping the core did allow for a somewhat higher NA but often changed other properties needed for specific applications. In this case a highly Ge-doped core was clad with a pure silica cladding leading to base NA values of about 0.33. These cores were generally sensitive to ultraviolet wavelengths and also had potential thermal mismatch problems limiting effective core size and power handling.

Recent development of new methods for preform production as well as new optical fiber structures have now made it possible to make more robust all silica core/clad fibers with numerical apertures for pure silica cores approaching 0.30 and with doped silica cores approaching 0.60. Properties of high NA optical fibers produced with doped silica cores are presented and their benefits for photon processing in microelectronics and photonics are discussed below.

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. 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.

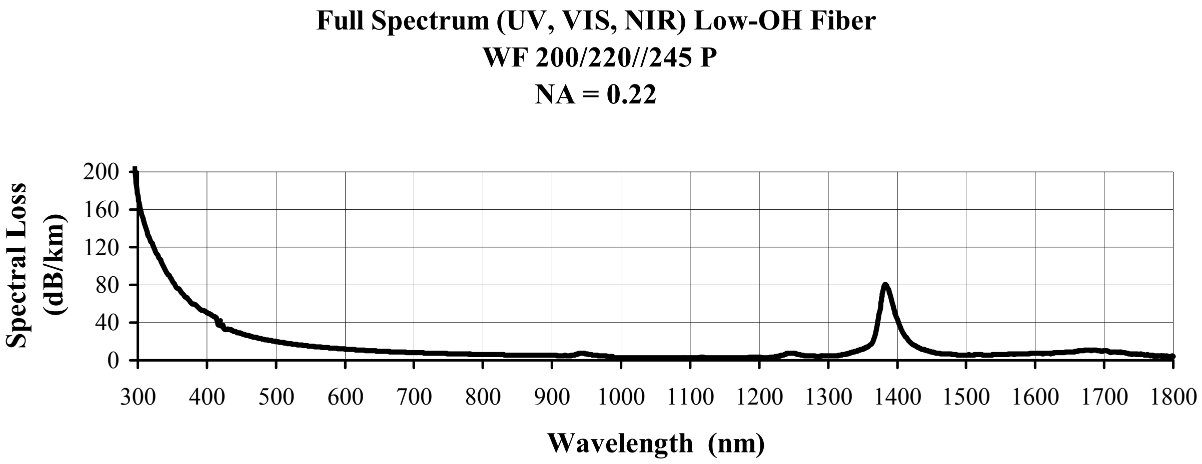
Full Spectrum (UV, VIS, NIR) Low-OH Fiber
WF 200/220//245 P
NA = 0.22

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

Figure 2 shows the typical 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[1] 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.

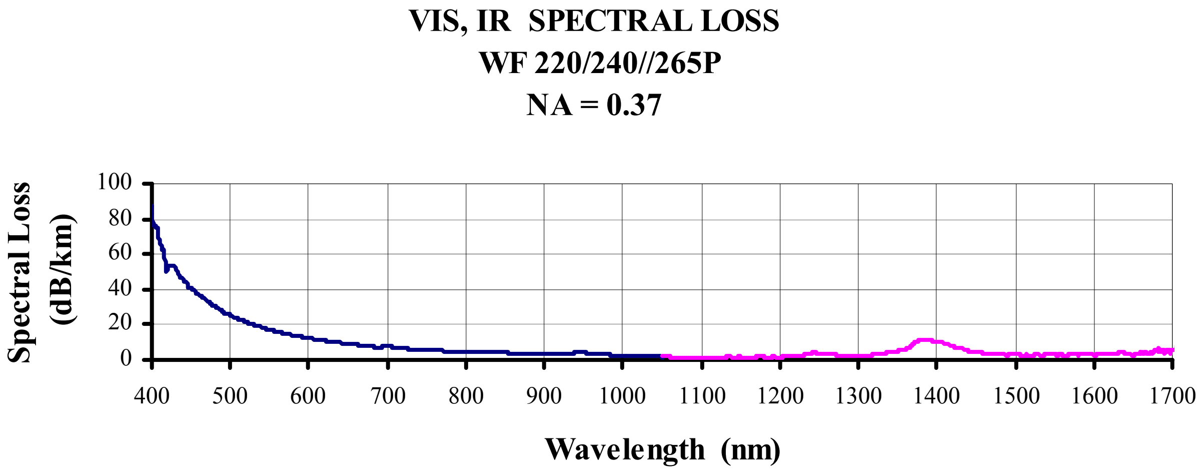
VIS, IR SPECTRAL LOSS
WF 220/240//265P
NA = 0.37

Figure 2: Visible, near infrared spectral loss for 0.37 NA low-OH fiber

Figures 3 and 4 show the visible and near infrared spectral loss for fibers with NA values of 0.47 and 0.56. The spectral loss behavior is essentially similar to the fiber measured in Figure 2. All have Ge-doped silica cores and F-doped silica claddings.

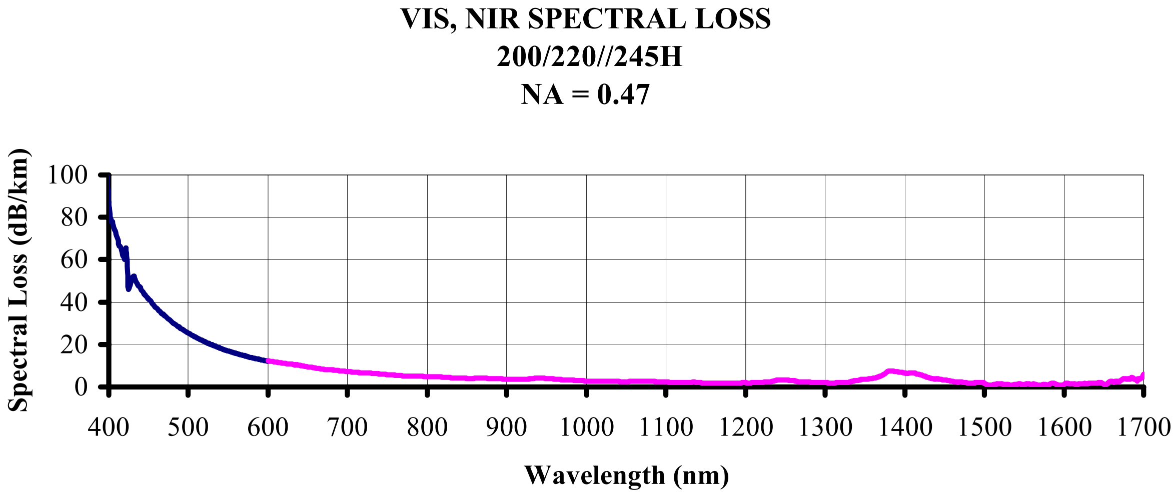
VIS, NIR SPECTRAL LOSS
200/220//245H
NA = 0.47

Figure 3: Visible, near infrared spectral loss for 0.47 NA low-OH fiber

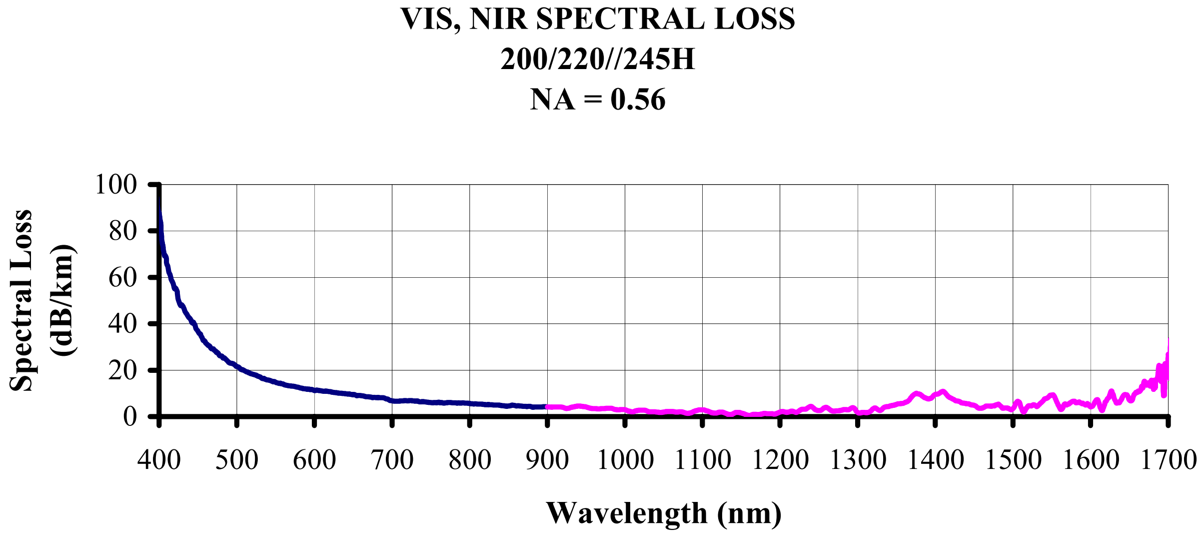
VIS, NIR SPECTRAL LOSS
200/220//245H
NA = 0.56

Figure 4: Visible, near infrared spectral loss for 0.56 NA low-OH fiber

Figure 5 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, germanium-doped silica/fluorosilica fibers at 0.37 and a new variation of the latter which has an NA of 0.56.

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 = 0.37 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.

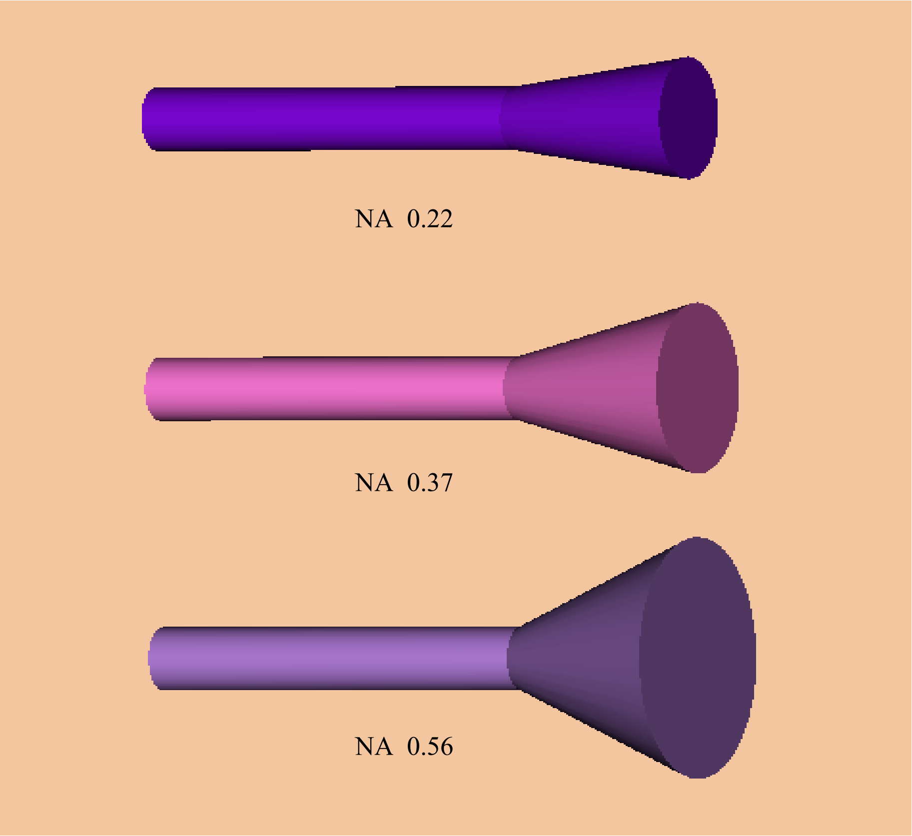

Figure 5: Schematic representation of the Numerical Aperture of selected optical fibers

4. DISCUSSION

Generally high power diode laser operate in the visible to near infrared [NIR] ranges of the spectrum. As a result, germanium doped silica cores can be used for most applications. Within a laser package, size and robustness are related to the size of the optical fiber which is used to deliver the laser beam and the amount of optical components needed to achieve and maintain efficient coupling from the laser source to the optical fiber. Lastly, in many applications, especially remote spectroscopy, where the power transmitted is low, it is critical to have very low loss optical fibers in order to capture and transmit the incoming signal with sufficient power to accurate measurement and analysis. Since the fingerprint region lies primarily in the NIR or visible ranges, again an all silica, germanium doped core, optical fiber is an excellent choice. High NA, low loss optical fibers are a benefit in each of these cases. The problem, however, has been that thermal mismatches between doped and undoped silicas have placed serious restrictions on fiber sizes that can be used for high power applications and on the numerical apertures [acceptance angles], for which stable fibers could be produced, for all applications.

The optical fibers, described herein, have been made with new methods of preform production and fiber production and some include a new structure. As seen in the results above, the basic spectral properties are essentially similar to earlier fibers having the same chemical materials. These fibers, which are thermally stable over a broader temperature range than are their protective coatings, have much larger NAs allowing for improved coupling of optical components. Having silica core and cladding makes these fibers a preferred choice for high power transmission systems.

As implied earlier, coupling of optical components can be improved in a number of situations by the use of high NA, low loss fibers. Some examples are given below, beginning with the fairly obvious case of remote spectroscopic sampling. Generally, low power signals are projected through a distance to a sample and a return signal is gathered, and returned to a detector system, where it is analyzed as required. Because the return signals especially are usually weak, a low loss medium is required to transmit sufficient signal to activate the detectors. For accurate sampling a larger area/volume of sample is preferred. Here the large NA can be used to excite a broader area/volume and the large NA also facilitates acceptance of return signal from a broader area.

In the design and functioning of compact laser systems, high NA all silica fibers can be used for delivery fibers, permitting a smaller dimensioned fiber to capture all the laser's power output, possibly without resort to lenses or other optical components. This reduces the size of the package and can improve reliability also by having a simpler less-component system with consequently less critical parameters and less items which could cause the system to go out of specification. The use of tapered fibers to increase power carrying capacity and power density at a treatment site can also be aided significantly by high NA fibers. Here the benefit is that a larger reduction in diameter is possible with less energy loss through the tapered section, assuming the incoming laser light is not fully filling all the modes in the fiber. As the beam strikes the walls in the transition zone, more light remains internally reflected rather than entering the lossy modes near the cladding or even being refracted out of the fiber.

In general, the output from a fiber can be used from near contact to longer distances from the exit of a fiber end. Although a higher NA beam will be more divergent, a smaller fiber diameter will project initially a smaller spot near the fiber end. In applications such as laser marking or ablation this may be critical to get the desired patterns. Laser welding may be aided by having a larger beam with a somewhat diffuse edge. Stronger better welds can result by having thermal distribution around the seam which diminishes slowly at first from the seam, permitting some adjustment in the material on both sides of the seam to enhance stability.

These represent some of the benefits which become possible in photon processing systems in microelectronics and photonics when low loss, high numerical aperture, optical fibers are available to the designer and end users.

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