High Numerical Aperture Silica Core Fibers

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ABSTRACT

Many medical applications have need of 'broad' irradiation patterns, but benefit from small diameter fibers to provide minimal invasive surgery. These applications also benefit from using the low intrinsic loss character of silica based core material as well as the power capability of a silica/silica construction. Pure silica core, all silica optical fibers are now available with an NA of 0.30 $\pm$ 0.02. Variations include fibers with non-solarizing ultraviolet transmission as well as fibers with transmission through the near infrared [IR] region of the electromagnetic spectrum. Additionally ultra high NA fibers with silica cores and silica/silica structures are now available for use in the visible and near IR regions with effective NAs higher than 0.6. Properties of these fibers are presented and the advantages over other fibers and potential medical applications are also discussed.

1. INTRODUCTION

Medical applications require a range of geometries, clad-core ratios and numerical apertures [NA] 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 larger the NA available. the smaller the clad-core ratio or the smaller the fiber core can be. Smaller cores and core clad ratios lead to the less materials expense incurred and more flexible fibers.

Smaller dimensioned optical fibers also permit the use of smaller catheters enabling associated surgery procedures to be less invasive. Small systems also can require broader illumination from optical fibers which may be minimized in number and/or in size as well. For UV applications pure silica core, all silica optical fibers are the most reliable and have the best transmission. Generally high power transmission also requires the excellent chemical stability of all silica optical fibers. 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.

Medical applications for lasers and for optical fibers continue to grow through time. Much of this growth is spurred by the development of more minimally invasive procedures, which put greater demands on using the smallest feasible optical fibers and systems. At the other end of the spectrum of uses, are the new medical applications/procedures which use short pulsed radiation at very high power levels and power densities. Large diameter fibers are often used because of the power densities. Even here the ability to lower core sizes is welcomed because of their improved handling characteristics.

Below we report on new optical fibers drawn from preforms that have been made by improved vapor deposition techniques which permit the much higher NAs for fibers with pure silica cores. Numerical apertures can be as high as 0.30 which corresponds to an acceptance angle of 35 degrees, with both high OH and low OH pure silica cores. Additionally new fiber structures in conjunction with newly fabricated preforms permit the drawing of fibers with germanium-doped cores having NA values as high as 0.56 and effective NA even greater for low power applications where the fibers can be overfilled. Optical properties of these high NA, low loss optical fibers are presented below and discussed in light of possible medical applications that would benefit from these fibers.

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 were measured for low OH fibers along with the UV and VIS spectral losses for 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, for short and 60-200 m for long. 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.

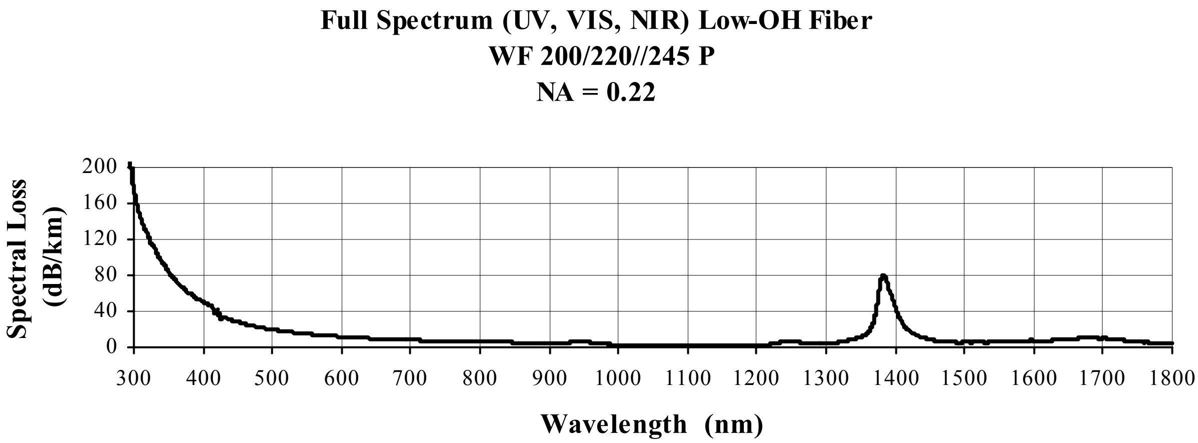

Figure 1: Full spectrum (UV, VIS, NIR) low-OH fiber

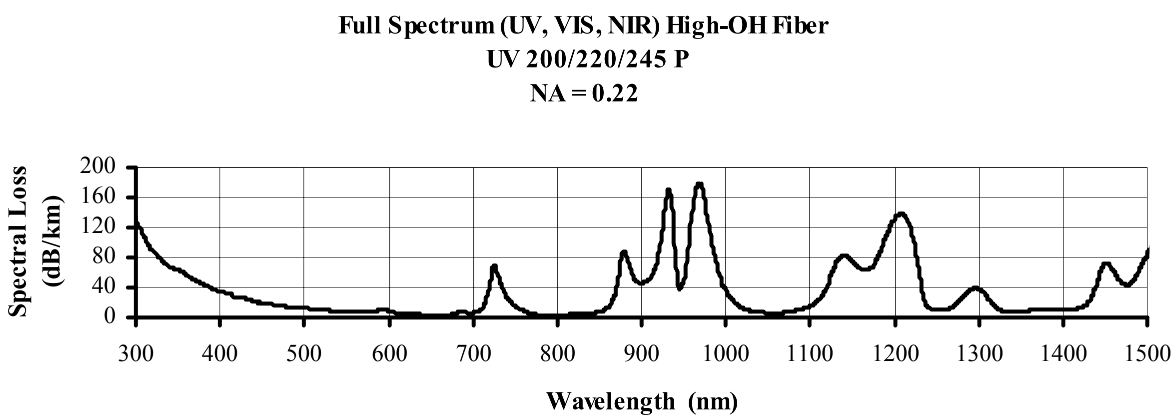

Figure 2: Full spectrum (UV, VIS, NIR) high-OH fiber

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.

UV-VIS-NIR SPECTRAL LOSS
UV 200/220//245 P
NA = 0.30

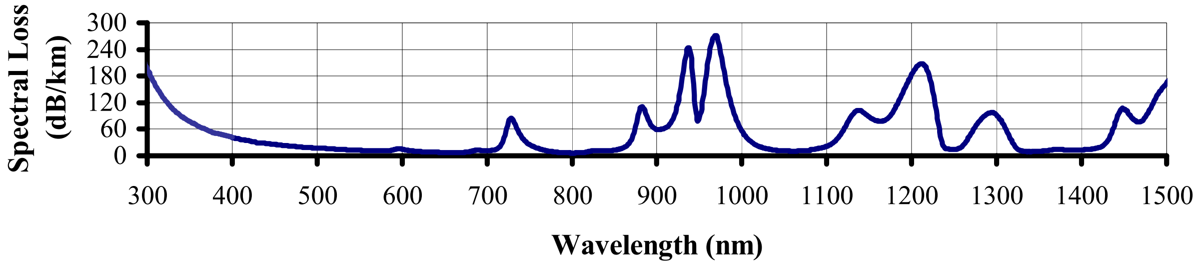

Figure 3: Ultraviolet, visible, near infrared spectral loss of 0.30 NA high-OH fiber

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.

VIS, NIR SPECTRAL LOSS
WF 200/220//245P
NA = 0.30

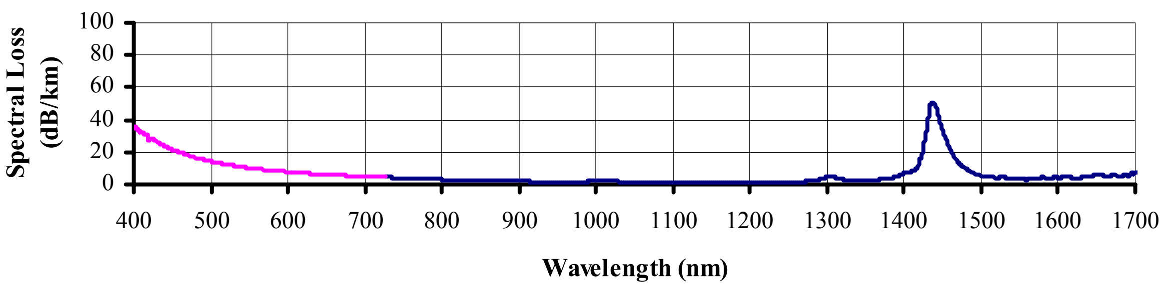

Figure 4: Visible, near infrared spectral loss of 0.30 NA low-OH fiber

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.

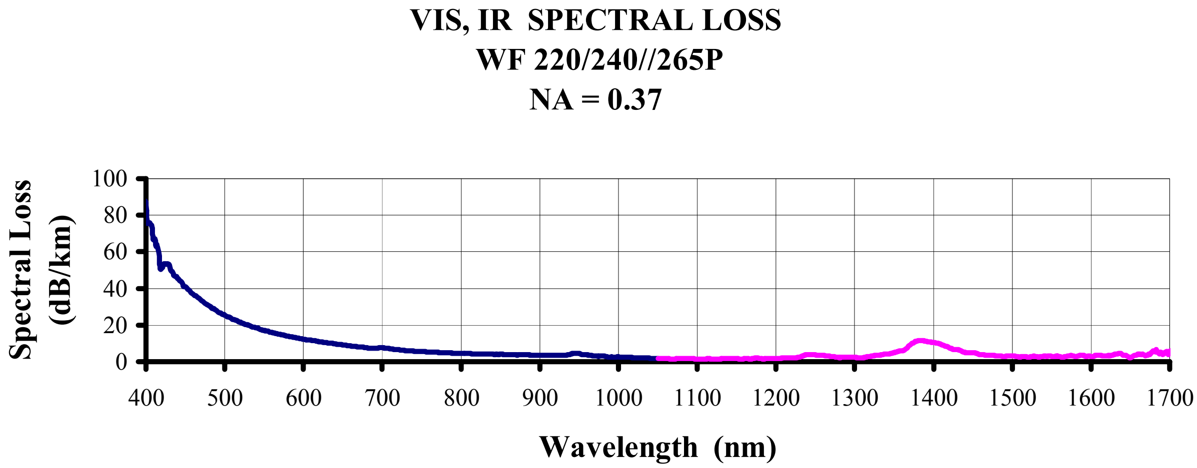

Figure 5: Visible, near infrared spectral loss for 0.37 NA low-OH fiber

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.

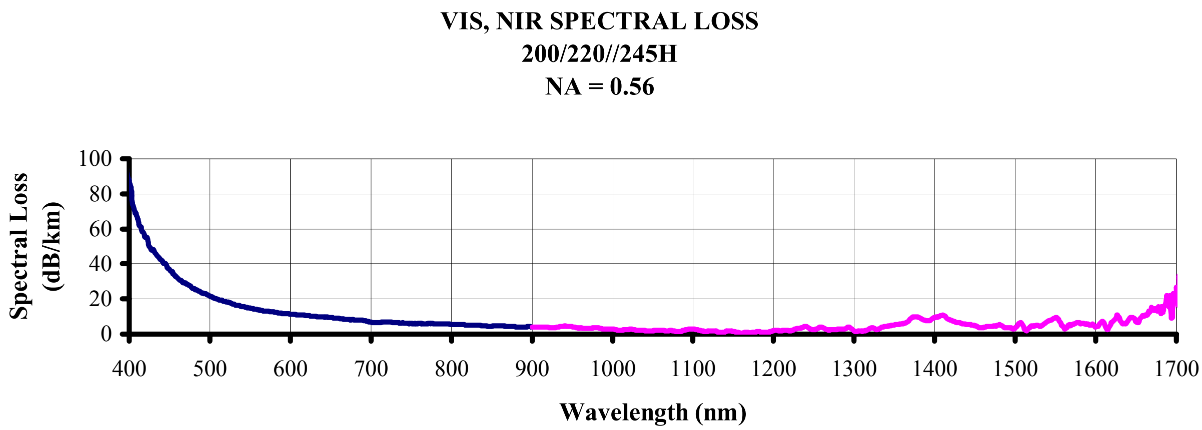

Figure 6: Visible, near infrared spectral loss for 0.56 NA low-OH fiber

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 86% 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.

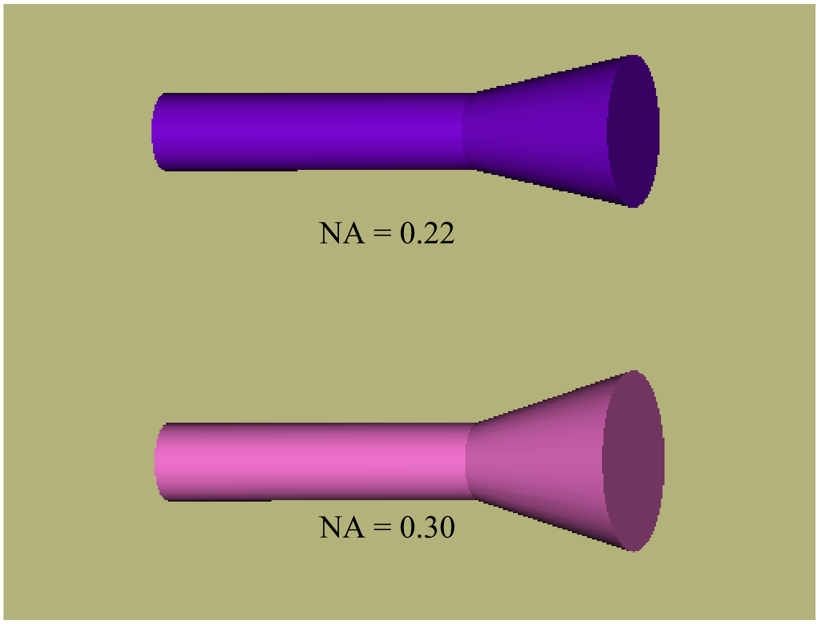

Figure 7: Schematic representation of the Numerical Aperture of selected optical fibers

4. DISCUSSION

The first thing to note, is that the spectral losses of the high numerical aperture (NA) optical fibers are essentially the same as for optical fibers with normal NAs, having the same chemical materials. Secondly, since the surface area of the acceptance circle is dependent square of the numerical aperture value, even small increases in the value lead to much larger acceptance cones, as noted for some examples in the Results section. Lastly, the uses and implications for the pure silica core fibers, which are now available with up to an NA of 0.30, are discussed first below. The uses and implications for the germanium-doped core fibers, which can have an NA up to 0.56 or effectively higher when fibers are overfilled and over-launched, are then discussed.

Both high OH as well as low OH, <3 ppm, pure silica core fluorosilica doped clad optical fibers are available in numerical apertures as high as 0.30 for high laser power transmission as well as other applications. In this numerical aperture range it is also possible to get non-solarizing optical fibers for transmission of high power uv sources, laser or otherwise. Laser surgery, laser ablation, laser cutting all can benefit from the power carrying capacity of all silica fibers, especially in pulse mode. The larger NA fibers benefit those applications where a large area needs to be treated. By using the fiber with its tip in contact or very near the treatment site the power density is maintained essentially at the size of the optical fiber's core. Most such medical applications are not sensitive to the quality of the laser beam, but rather the spot size and power density only. Being able to reduce the size of the fiber while carrying all the power from the laser or other light source can thus lead to higher power densities at the treatment site.

Interstitial and contact irradiation methods can particularly benefit by the broader NA fibers. Since body tissue is primarily water, the refractive index of the medium is about 1.33 which causes the angle for exit to be significantly reduced from that calculated for exit into air. For example, in the case of fibers with an NA of .22, the dispersion angle in a water based medium is only 19 degrees instead of 25.4 degrees and the circular surface area of the projection at some distance from the fiber end is reduced by 56.5%. A fiber with an NA of 0.30 would yield a dispersion angle in a water based medium of 24.6 degrees, very similar to the emission/dispersion of the 0.22 NA fiber into an air medium. The latter also translates into a circular surface area of the projection to essentially similar for the 0.30 NA fiber into water as that of 0.22 NA fiber into air. Tissue welding as well as underskin treatment of wrinkles, etc. can thus benefit from using these fibers with higher NA values.

Another area lies within the laser device, where for example a high power diode laser usually has several emitters whose power needs to be coupled into fibers and eventually into a delivery fiber. The new diode laser emitters have higher quality laser beams though still highly multimode. Whereas before in the fast axis the dispersion angle was usually over 40 degrees, now dispersion angles as small as 32 degrees, well within the acceptance angle of a 0.30 NA fiber or even a 0.28 NA fiber. Extra optics to treat the fast axis dispersion can now be eliminated making for a more compact unit and possibly more robust package. The delivery fiber questions are dealt with further below.

Turning now to the germanium-doped core fibers with ultra high NA values, we note that these fibers are primarily very low OH fibers, typically < 0.5 ppm, useful for most wavelengths beyond about 400 nm.

The ultra high NA fibers described herein can be used as delivery fibers, especially for high power diode laser systems. The benefits arise because of requirements of phase space to allow reduction in size from the dimension of a bundle of coupling fibers to a delivery fiber size such that the dispersion angle of the smaller dimension the multiple of the reduction in size. In other words the product of NA and fiber bundle size is equal to the product of the delivery fiber size and its NA.

Other uses of the large NA fibers are in illumination applications especially in cases where the fiber end is not in air. For example less illumination fibers might be used in an ophthalmology application if the NA of the fiber can be over 0.50. Hands-free helmet type illuminators are another area that benefits from being able to use these ultra high NA optical fibers.

Medical applications which generally need to treat larger areas and whose light sources are not in the ultraviolet can be more efficiently performed with larger NA fibers a more area is covered by the fiber output. Examples might be Photodynamic Therapy, wound healing, and general interstitial radiation therapy. The latter especially for reasons analogous to the discussion above for pure silica core high NA fibers can benefit greatly from large NA optical fibers whether the medical action is by photons directly or indirectly as converted to thermal phonons. Some aspects of tissue welding which are shared with wound healing such as a need to treat areas much larger than the output of a standard optical fiber can easily be seen to benefit from fibers with larger NA values.

A special point with reference to the ultra low OH grades of these fibers is that they can be used in medical applications with lasers or other sources operating wavelengths above 2 μ. Some variations have been used to transmit radiation at wavelengths as high as 2.4 μ. They thus provide good transmission in a very desirable wavelength and with the ability maintain high power densities.

Photons are available from sources other than lasers. Coupling photonic energy in many cases using lamps, high brilliance LEDs or other high power LEDs can be a challenge, because the sources often have broad beams and are projected in highly divergent beams from the source. Rather obviously optical fibers with large to ultra-large NAs would be a benefit in capturing the photons and transmitting them to some remote application area, such as inside a patient or to several patients in adjacent stations/rooms/beds.

In summary, optical fibers are now available for use or in the design of photonic treatment systems that have the following properties: NA values up to 0.30 for pure silica core, fluorosilica doped cladding, high or low OH, in non-solarizing uv grades; NA values up to 0.56 for germanium doped core, fluorosilica doped cladding, low to ultra low OH grades. These open up more efficient uses of fiber optics and photonics in a wide range of medical applications and treatments.

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