Reliable Large Acceptance Optical Fibers for High Power Transmission

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ABSTRACT

Typically, output from high power, diode lasers and arrays must be transported to a final application/treatment site, whether the application is industrial, military or medical. Many demands are placed on optical fibers to couple the laser output into their structures and to transmit the power to the application site. All silica fibers become much more expensive as the diameter of the fiber increases to handle larger spot sizes and higher NA beams, especially from diode arrays. High strength, low fatigue Hard Plastic Clad Silica fibers provide benefits of larger Numerical Aperture (NA), more flexibility and less strain at the core-clad interface. Fibers with these characteristics and available in both high OH and low OH versions for UV and NIR spectral regions are described. Short and long term strength, and spectral properties are presented. Results for a new high NA version are also be presented.

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. 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 potential 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. For example, a highly Ge-doped core, clad with a pure silica cladding, can have an NA of about 0.33. These cores are generally sensitive to ultraviolet wavelengths and also have potential thermal mismatch problems limiting effective core size and power handling.

An alternative, which uses the advantages of pure silica core and has high numerical aperture version, is Hard Plastic [polymer] Clad Silica (HPCS) fiber. They are available for use in both UV and VIS/NIR spectral regions, dependant primarily on the OH levels in the silica used as the core. The spectral behavior and mechanical reliability of this fiber type are presented below along with a review of their advantages and liabilities as compared to all silica optical fibers.

2. EXPERIMENTAL

The UV and VIS spectral losses of high-OH Hard Plastic Clad Silica (HPCS) fiber were measured along with the NIR and VIS spectral losses of low-OH HPCS fiber with nominal core diameter for both types was 600 μm. High-OH fibers typically have ≥600 ppm of OH, while low-OH fibers typically have <2-4 ppm of OH.

A "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.

The "cutback" method consisted of using two pieces of same-type fiber with a length ratio of about 1:4 or 1:5. Long lengths of over 25 m were measured via a Tektronix ODTR, and 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. More complete details on the spectral measurements were reported earlier[1].

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 180 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 mechanical property primarily reported is the dynamic strength as measured by a universal testing machine and plotted on a Weibull plot. Gauge length was 1 meter. The fiber is stretched while horizontal and anchored at the two ends by wrapping several loops around a tapped mandrel of approximately 10 cm diameter. About 1.7 meters of fiber is consumed per trial. Results presented below are generally from one or two fibers where 15-20 samples are taken from a specific fiber run. Tests were made at ambient temperature and relative humidity. Temperatures ranged in the 20-27 C, and relative humidity [RH] primarily was 30% ± 7%, although some samples were tested with RH at 72%. Strength data are plotted according to the generally accepted Weibull approach.

3. RESULTS

Figure 1 shows the typical spectral loss of standard, low-OH HPCS fiber (HWF) with core/clad geometries of 600µm/640µm and a numerical aperture (NA) of 0.37 from the wavelengths 400 nm to 1700 nm. This fiber has pure undoped silica as the core material and the 'standard' hard plastic cladding.

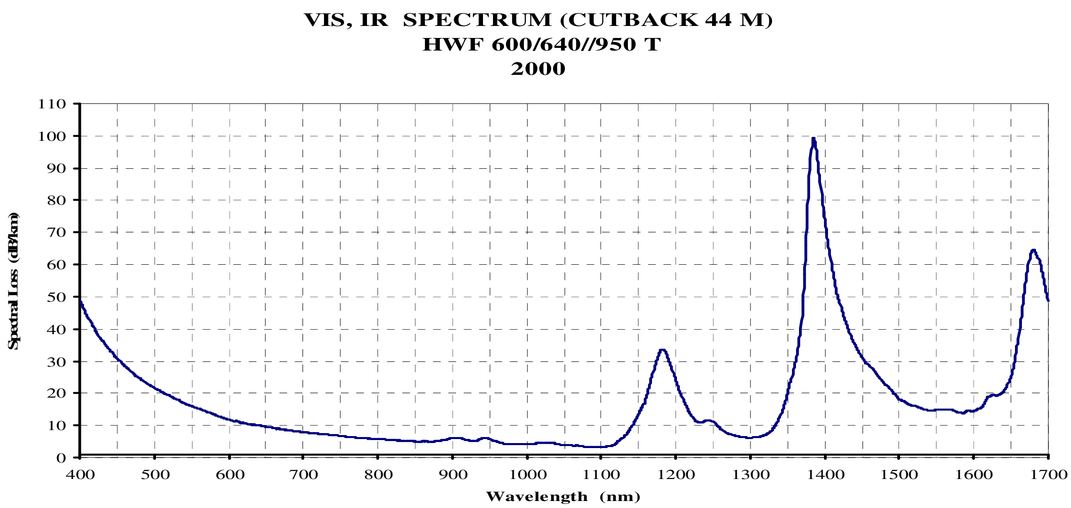

Figure 1: Full spectrum (VIS, NIR) low-OH fiber, NA = 0.37

Figure 2 shows the typical spectral loss of standard, high-OH HPCS (HUV) fiber with core/clad glass geometries of 600µm/630µm and a numerical aperture (NA) of 0.37 from the wavelengths 300 nm to 1200 nm. This fiber has pure undoped silica as the core material and the 'standard' hard plastic cladding.

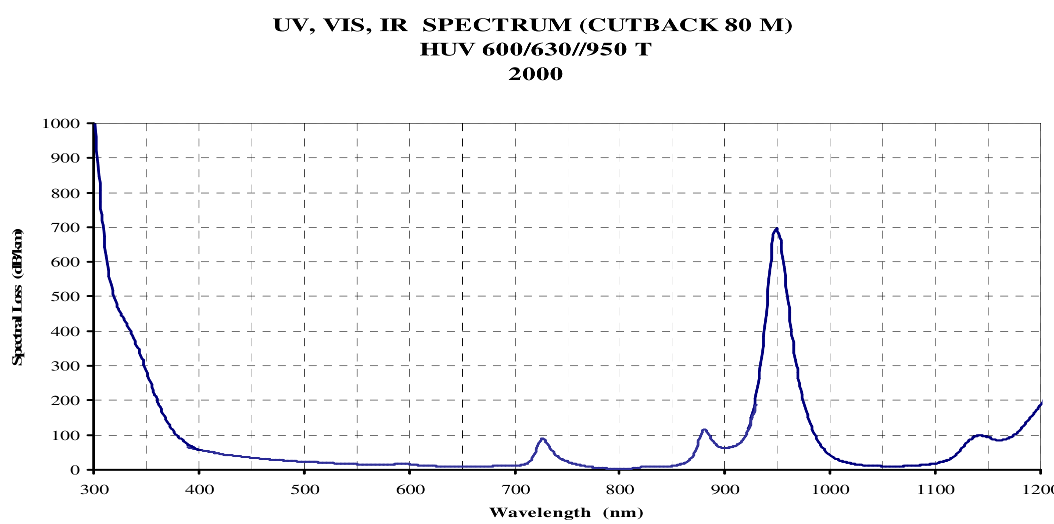

Figure 2: Full spectrum (UV, VIS, NIR) high-OH fiber, NA = 0.37

As a measure of the reliability of these fibers, we present dynamic strengths measurements for fibers make over a 5 year period and including a fiber tested and retested during this period.

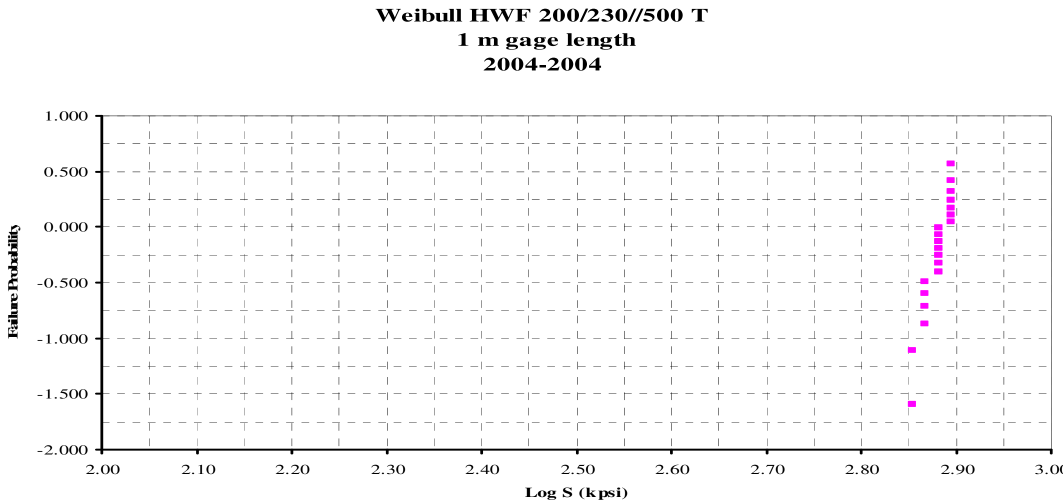

Figure 3: Weibull Plot of dynamic strength of Optran HPCS fiber, NA = 0.37

Figure 3 presents the data for samples of standard Optran[2] HPCS fiber produced in 2004 and tested in 2004. Note that log S = 2.85 is a strength of 4.88 GPa and log S = 2.90 is a strength of 5.48 GPa.

In Figure 4 the Weibull plot compares fibers drawn in 1999 [left points black], and in 2004 [right points, shaded] Note that log S = 2.80 is a strength of 4.35 GPa.

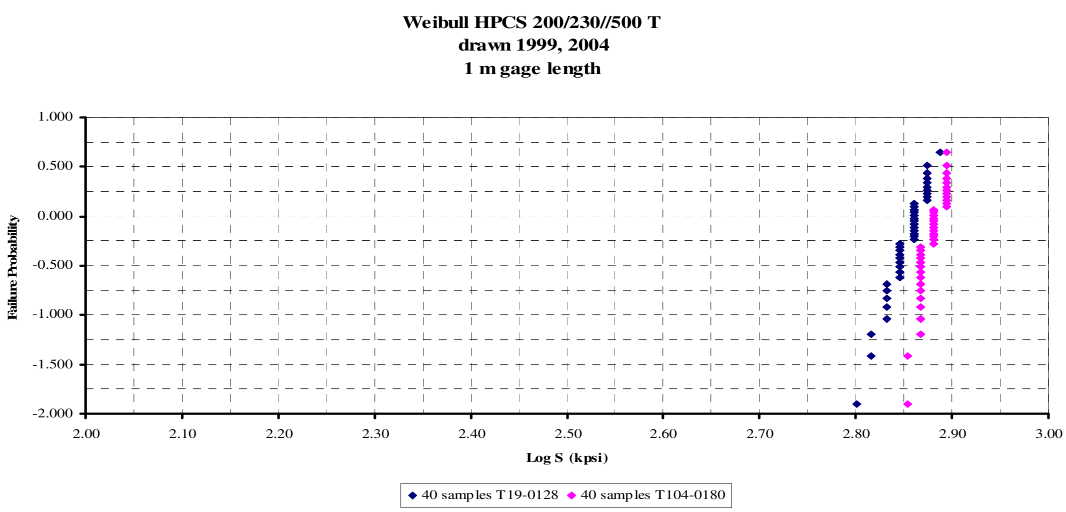

Figure 4: Weibull Plot of standard Optran HPCS fiber; drawn ‘99[left], drawn ‘04[right]

In Figure 5, the Weibull plot compares strength for a fiber drawn in 1999, tested in 2000 [circles] and again in 2004 [shaded triangles] after storage in varying humidity (10-80% RH) on spools under about 0.1 GPa (15 kpsi).

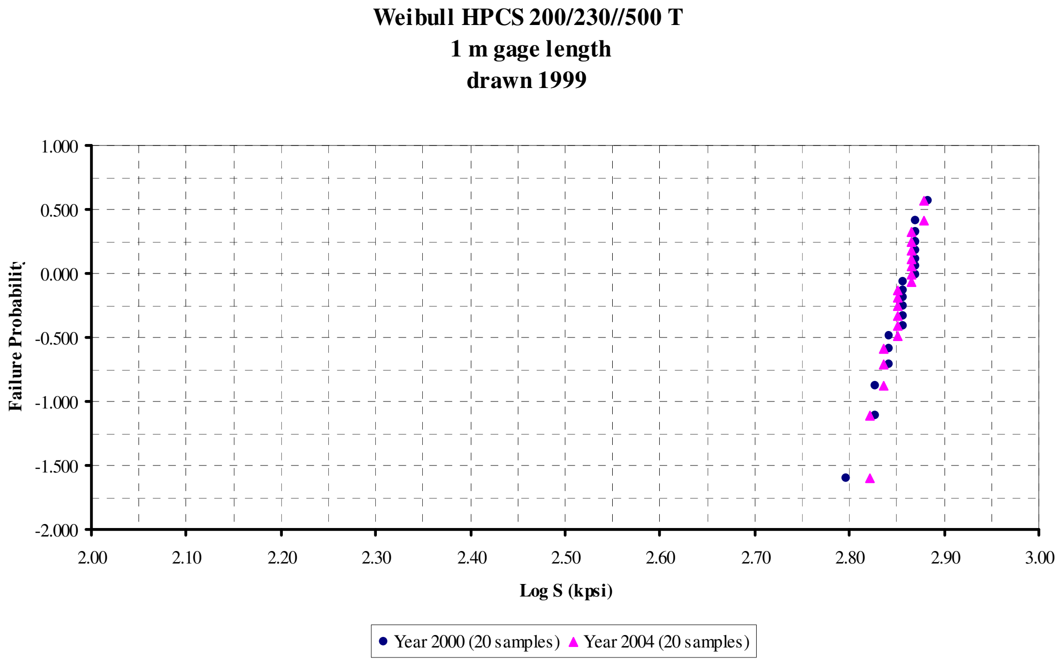

Figure 5: Weibull Plot of std. Optran HPCS fiber; test '00[circle], test '04[triangle]

Finally, we present spectral data and a first set of strength data for a newly developed high NA version of the Optran HPCS, whose cladding is essentially as tough as that for the standard NA HPCS.

Figure 6 shows the typical spectral loss of low-OH HPCS fiber (HWF) with core/clad geometries of 200µm/230µm and a numerical aperture (NA) of 0.37 from the wavelengths 400 nm to 1700 nm. This fiber has pure undoped silica as the core material and the 'standard' hard plastic cladding.

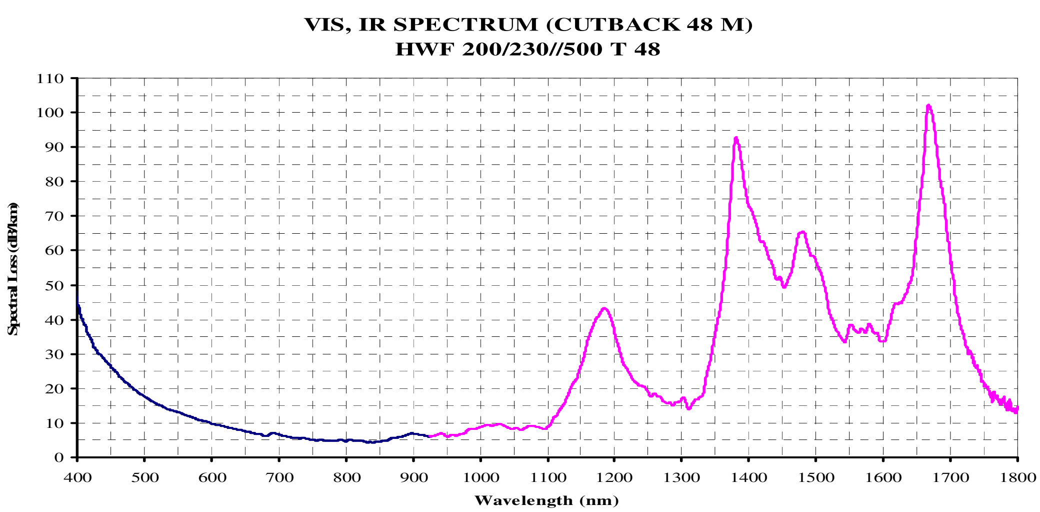

Figure 6: Full spectrum (VIS, NIR) low-OH fiber, NA = 0.48

Lastly, Figure 7 presents the data for samples of high NA HPCS fiber produced in 2004 and tested in 2004. Note that log S = 2.75 is a strength of 3.88 GPa, log S = 2.80 is a strength of 4.35 GPa, and log S = 2.85 is a strength of 4.88 GPa.

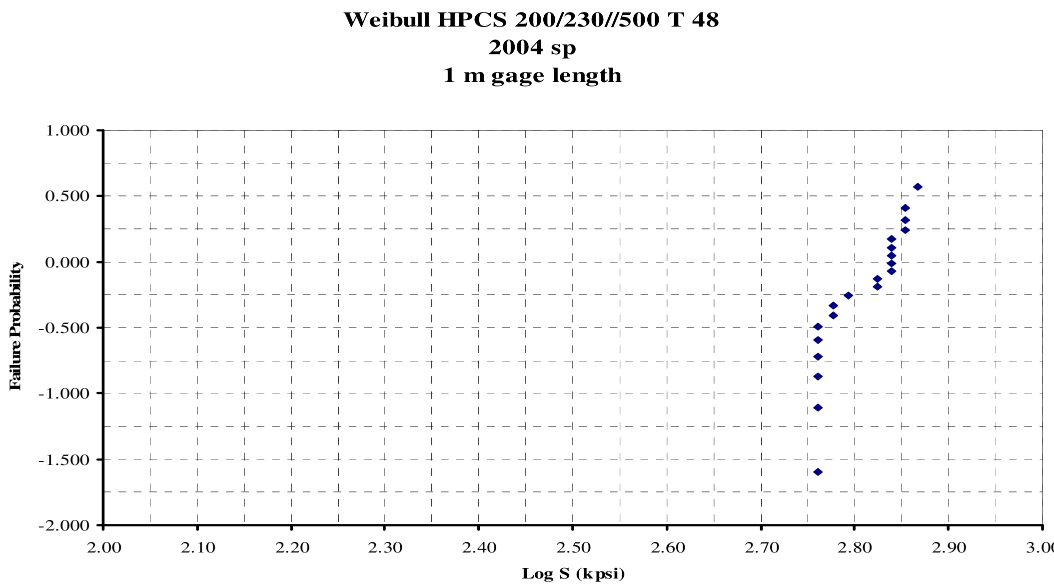

Figure 7: Weibull Plot of dynamic strength of high NA Optran HPCS fiber, NA = 0.48

4. DISCUSSION

As implied earlier, coupling of optical components can be improved in a number of situations by the use of high NA, low loss fibers. In the design and functioning of compact laser systems, high NA HPCS 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, fewer-component system with consequently less critical parameters and less items which could cause the system to go out of specification.

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. In particular the addition of a more robust 0.48 NA HPCS fiber should broaden the designer's options.

To summarize, HPCS fibers are shown to be reliable, robust having high dynamic strengths with little change in strength or distribution of flaws after storage at about 0.1-0.2 GPa [10-25 kpsi] for up to, at least, 5 years. Their strengths are remarkably reproducible even for lots made in different years. Their dynamic strength and fatigue behavior are comparable to all-silica fibers. Weibull mean strengths are above 4.4 GPa [>600 kpsi]. Prior studies have indicated a static fatigue parameter of > 15. Power capacity approaching 1GW/cm2 under proper conditions. Their lighter weight can be of some benefit for non-stationary high power laser stations.

A new high NA HPCS is introduced here. It has spectral and strength properties similar to the standard NA HPCS fibers. The latter is significantly more robust than earlier versions. With the NA= 0.48, it is now possible to provide a larger target for collecting the output from multiple laser sources, e.g. diode laser arrays, and delivering high brightness power to a site, by use of smaller core size.

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REFERENCES

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1. B. J. Skutnik and H. Park, "Cladding Effects on Spectral Transmission of Optical Fibers for Medical Applications", SPIE Proc. **4616**, 180 (2002).
2. Optran is a trademark of CeramOptec Industries/Biolitec.