All Silica, Non-Solarizing Optical Fibers for UV Medical Applications

Bolesh J. Skutnik and Brian Foley

CeramOptec®, Inc., East Longmeadow, MA 01028

ABSTRACT

Optical fibers and fiber bundles have been developed for UV applications in general but have specific benefits for UV applications within medicine such as excimer angioplasty and UV perforation of the heart wall in heart bypass operations. Optical fibers have been tested for transmission changes at 193 nm, 214 nm, 253 nm and 365 nm. Whereas standard synthetic silica optical fibers developed color centers within 10,000 pulses of 193 nm energy, the new CeramOptec fibers were observed to experience only minimal changes in attenuation after 100, 000 pulses. Similarly under constant irradiation by a high power deuterium lamp only minor changes in the attenuation at both 214 nm and 253 nm were observed for the 'non-solarizing' UV fibers after 121 hours, whereas standard UV fibers lost up to 50 % after only 24 hours of exposure. Fiber bundles have been produced which can stand up to the elevated temperatures experienced at the source end when strong UV sources are needed for specific applications. Test results and information on the testing as well some information on the fibers tested is given below.

Keywords: UV optical fibers, non-solarizing optical fibers, fibers for excimer lasers

1. INTRODUCTION

There is a growth in the use of excimer lasers for medical applications. This has lead to the need to address the problems associated with the damage and transmission properties of silica fibers in the UV region particularly for high power and for high repetition pulsed transmission. Although there are a number of commercially available fibers, which can efficiently handle transmission of relatively low intensities of laser radiation, there still exist difficulties for high power radiation transmission. For example, standard synthetic silica optical fibers with high-OH levels offer low attenuation, high transmission, in the 215-254 nm spectral range, but on exposure to an unfiltered deuterium lamp these fibers drop to less than 50% of the original transmission within 24 hours of continuous irradiation. Similar though less severe and less permanent losses have been observed at 308 nm. Also the standard UV fibers tend to develop significant color centers, visible to the eye, by 10,000 or less pulses of excimer laser radiation at 193 nm at fluences of about 50 MW/cm^2. Typically this behavior upon exposure to deep UV light is called "solarizing" behavior. Changing transmission capability of the optical fiber during transmission of UV radiation in a medical treatment creates problems for the practitioner trying to regulate the exposure of a patient to the UV radiation.

In the UV spectral region, below 350 nm wavelengths, synthetic silica optical fibers, having undoped, high-OH cores and fluorine-doped claddings, which have a lower refractive index, are the primary candidates. The basic attenuation of these fibers is generally acceptable[1-3]. The induced losses, primarily arise because of transient or permanent changes in the silica, which are due to non-

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linearities arising from two photon absorption. These losses must be considered and dealt with for transmission of high intensity UV laser light[4-11], which is required for the developing applications of UV lasers in medicine such as excimer laser angioplasty and perforation of heart muscle during bypass surgery. These new applications generally require high pulse energies and short pulse durations, which create very high power densities within the transmission medium.

2. EXPERIMENTAL

The fibers used in the experiments referred to below were drawn using essentially standard techniques. The basic core/clad structure employed a pure undoped silica for the core and a fluorine doped silica cladding, basically in common with most other all silica optical fibers. The preforms, however, were made using a proprietary procedure for the modified Plasma Chemical Vapor Deposition of silica, different from that of Heraeus or Heraeus-licensed technology. The OH levels for the fibers tested herein were ≥ 800 ppm. The core diameters of the fibers were generally $\geq$ 400 μm with typically a clad to core ratio of 1.1 to 1. These fibers are available commercially as non-solarizing Optran® UV optical fibers[12], e.g. as UV400/440P used in the deuterium lamp study presented in Figure 1. The jacket for this fiber is a polyimide coating having a thickness of about 12 μm. All the results described herein were gathered from tests which were performed by researchers and engineers at unaffiliated clients' facilities.

The fiber bundles, used primarily in the long term exposure to UV light for this paper, were prepared with specially treated terminations where all organic materials have been removed. The all silica fibers are fused together to form a pattern of fibers slightly deformed into hexagonal shapes to provide a tight hexagonal packed structure with a minimum of dead space. These specially terminated fiber bundles are available in general for high power transmission especially where accompanied by high temperature demands.

The effects of UV light energy at 193 nm, 215 nm, 254 nm, and 365 nm have been observed, with some additional data at other wavelengths. At 193 nm an excimer laser source was employed. The optical fibers were exposed to pulses of 15 nsec duration and input energy of 1.5 mJ. The effects of UV power transmission on optical fibers' transmission behavior at the other wavelengths was observed using continuous radiation sources. These sources were either an unfiltered deuterium lamp or an unfiltered high pressure mercury lamp. Prior work on preforms and fibers developed earlier in the development of the current PCVD process dealt with the fourth harmonic of Nd:YAG lasers, 266 nm[11], and with the 308 nm and 248 nm outputs of XeCl and KrF lasers respectively[8].

The value of the transmission T for a fiber of length l is given, as in previous publications[6,8,9], by:

$$1/T = \exp(\alpha_0 l) + \alpha_1 I_0/\alpha_0[\exp(\alpha_0 l) - l]$$

where α_0 is the small signal attenuation coefficient, α_1 is the two-photon absorption coefficient and I_0 is the input intensity. The coefficients are dependent on wavelength so fiber transmission at each selected wavelength must be measured as a function of input energy density to obtain their values as was done in the prior publication[8].

The present paper's aim is to summarize transmission results obtained over the wide range of deep UV and near UV wavelengths thus this paper will not go into a detailed analysis of the components of the transmission, which will be the topic of a future paper.

3. RESULTS

In Figure 1 the observations of transmission through a UV400/440/465P fiber are presented. As indicated an unfiltered deuterium lamp was used. The data were obtained over a six day period. The spectrum was monitored at 253.9 nm and at 214.6 nm. Over the 121 hours the transmission through the Optran fiber at 215 nm was substantially unchanged at about 92% of original, while for standard UV grade fibers a drop of 50% is experienced within 24 hours. The transmission at 254 nm appears to be slightly improved to about 110% over the 121 hour duration of the test. These results are a good indication that essentially no production or growth occurred in the E'-center defect, whose absorption peak is centered at 215 nm, for the new 'non-solarizing' CeramOptec optical fibers.

The Optran UV fiber exposed to repeated pulses of 193 nm laser light was a UV600/660/760/860N fiber. This is an all silica, 1.1 to 1 clad/core fiber with the composition and structure indicated in the previous section. It had a 50 µm thick silicone buffer and a 50 µm thick nylon jacket. The radiation was focussed onto a spot having a 425 µm diameter. The input pulse energy was 1.5 mJ or 1.1 J/cm^2 while the input pulse power was 70 MW/cm^2. The transmission was measured periodically and the transmission through the Optran fiber was found to be substantially unchanged after 100,000 pulses. In contrast most standard UV fibers experience significant degradation in transmission in less than 1000 pulses of light at this wavelength and lower input pulse energies. Under the conditions of the 100,000 pulse test a standard silica/fluorosilica [core/clad] UV optical fiber was found to be colored a deep red by about 10,000 pulses.

Another example of the improved transmission of UV light energy is provided in Figures 2 and 3. The first figure is a spectrum of an unfiltered mercury source as transmitted through a commercially available all silica fiber. The second figure is the spectrum transmitted through an Optran optical fiber with improved UV transmission. The transmission levels, y-axes in both figures, are presented in the same arbitrary units. A comparison of the two figures illustrates the improved transmission of the Optran UV fiber. The improvement is especially evident at the lowest wavelengths, below 230 nm, with the transmission ratio for the two fibers being 4/1 for the Optran fiber than for the standard fiber around 200 nm.

Finally the longest UV exposure testing has been made on specially developed fiber optic bundles using Optran UV fibers in a fused silica termination. As part of this long running evaluation of these "non-solarizing" fibers, including effects of sustained high temperatures, fiber bundles of 1m length have been subjected to from 500 to almost 25,000 hours of continuous radiation at 365 nm. The transmission changed by only about 7% after 200 hours and remained essentially constant from 400 hours onwards. The radiation source has a measured variability in output intensity of about ± 3%. Comparative measurements were made at several wavelengths as well as for the 360-370 nm range after approximately 1200 hours. The results are given in Table I below.

Table I

Wavelength range (nm)	Transmission after 1180 hours (%)
240-250	89.4
310-320	87.9
360-370	86.4
400-410	86.9
430-440	90.1

where the % 'transmission after 1180 hours' is the transmission relative to the initial transmission of the sample fiber bundle for the various reported wavelength ranges. All silica fiber bundles from other commercial sources were found to lose significantly more of their transmission capability and to have a continually increasing loss beyond 400 hours, i.e. little or no stabilization was observed at longer times. This application/test also has a problem in that high temperatures are present during the operation of the system.

4. DISCUSSION

Previous workers have determined that the E' centers and NBOHC are the primary defects created during high energy exposure to UV light in medium to high OH level silica materials[2,3,8,9,11]. The growth of absorptions at 163 nm and 248 nm are now well documented. These detrimental changes in the transmission properties of silica lenses and optical fibers have been called solarization effects. The aims of glass suppliers[13] and optical fiber manufacturers[1,8,11] as well as silica glass researchers[3,5,7,9,10] have been to identify the effects, quantify them and then work to reduce the solarization[14] of these products.

Plasma modified/enhanced CVD processes for creating all silica preforms have done much to improve the quality and reproducibility of the preforms. This processing, though, can introduce some potential sites or nascent defects that can increase sensitivity to solarization. Since most plasmas are oxygen rich, unless special care is taken, there is a modest probability that peroxy linkages will be incorporated into the preform during its manufacture. This is especially true if the OH level is being held down. Furthermore, most plasmas have associated with them intense UV emissions. These emissions irradiate the silica during the deposition process. This may be more significant during the deposition of the cladding over a solidified core. The exposure may also be enhanced if the consolidation process is carried out more or less simultaneously with the deposition process. The exposure of the preform during its forming may initiate defects or precursors to defects which are activated more easily when as an optical fiber they are exposed to laser generated UV light in a particular medical or industrial application.

Independent of the general method of fabrication of synthetic silica from $SiCl_4$, the chemistry and physics of the deposition, conversion and consolidation processes can affect the structure and distribution of intrinsic 'defects' as well as the structure of the glass[15]. These can include chemical moieties such as SiOH, SiH, SiCl, O_2, and Cl_2 in addition to the peroxy species mentioned earlier.

Interactions between these in the presence of UV radiation has been shown to display a variety of affects on the UV transmission of all silica optical fibers.

The present data are not adequate to allow mechanistic analysis for the latest version of Optran UV optical fibers. Proposed studies similar to those carried out on an earlier version[8] dealing in greater detail with color center formation and two photon absorption coefficients are in the planning stage. The current paper, however, does demonstrate the possible reduction in precursors for such defects by use of the proprietary plasma modified chemical vapor deposition techniques in the excellent UV transmission behavior recorded by outside workers, employing the UV fibers in their respective applications.

REFERENCES

1. B. Skutnik, W. Neuberger, J. Castro, V.P. Pashinin, L.M. Blinov, V.I. Konov and V.G. Artjushenko, "Silica Fibers with Enhanced UV Performance", SPIE Proc. **1649**, 55 (1992).
2. J.A. Harrington, "An Overview of Power Delivery and Laser Damage in Fibers", SPIE Proc. **2966**, 536 (1997).
3. K.-F. Klein, G. Hillrichs, P. Karlitschek and K. Mann, "Possibilities and Limitations of Optical Fibers for the Transmission of Excimer Laser Radiation", SPIE Proc. **2966**, 564 (1997).
4. R.S. Taylor, K.E. Leopold, R.K. Brimacombe and S. Mihailov, "Dependence of the Damage and Transmission Properties of Fused Silica Fibers on the Excimer Laser Wavelength", Appl. Opt. 27, 3124 (1988).
5. G. Mueller, H. Kar, K. Dorschel and H. Ringehan, "Transmission of Short Pulsed High Power UV Laser Radiation through Fibres Depending on Pulse Length, Intensity and Long Term Behavior", SPIE Proc. **906**, 231 (1988).
6. R.K. Brimacombe, R.S. Taylor and K.E. Leopold, "Dependence of Nonlinear Transmission Properties of Fused Silica Fibers on Excimer Laser Wavelength", J. Appl. Phys. **66**, 4035 (1989).
7. E.H. Nevins, "Alteration of the Transmission Characteristics of Fused Silica Fibers by Pulsed Ultraviolet Radiation", SPIE Proc. **540**, 421 (1985).
8. V.G. Artjushenko, V.I. Konov, V.P. Pashinin, A.S. Silenok, L.M. Blinov, A.M. Solomatin, I.P. Shilov, V.V. Volodko, G. Mueller, B. Schaldach, R. Ulrich and W. Neuberger, "Fused Silica Fibers for the Delivery of High Power UV Radiation" SPIE Proc. **1420**, 149 (1991).
9. V.I. Konov, V.P. Pashinin and A.S. Silenok, "Formation of Non-stable Color Centers in Fused Silica Fibers, Induced by High-power XeCl Laser Radiation", SPIE Proc. **1201**, 247 (1990).
10. P. Karlitschek, G. Hillrichs and K.-F. Klein, "Photodegradation and Nonlinear Effects in Optical Fibers Induced by Pulsed UV-laser Radiation", Opt. Comm. **116**, 219 (1995).
11. V.G. Artjushenko, V.I. Konov, N. Yu. Konstantinov, V.P. Pashinin, A.S. Silenok, G. Mueller, B. Schaldach, R. Ulrich, W. Neuberger and J. Castro, "Mechanisms of UV Laser Induced Absorption in Fused Silica Fibers", SPIE Proc. **1590**, 131 (1991).
12. Optran is a registered trademark of CeramOptec, Inc.
13. H. Fabian, U. Grzesik, G. Hillrichs, and W. Neu, "Optical Fibers with Enhanced Performance for Excimer Laser Power Transmission at 308 nm", SPIE Proc. **1893**, 124 (1993).
14. P. Karlitschek, K.-F. Klein and G. Hillrichs, "Suppression of Solarization Effects in Optical Fibers for 266 nm Laser Radiation", SPIE Proc. **2966**, 620 (1997).

15. V.Kh. Khalilov, G.A. Dorfman, E.B. Danilov, M.I. Gruskov and V.E. Ermakov, "Character, Mechanism of Formation and Transformation of Point Defects in Type IV Silica Glass", J. Non-Cryst. Solids 169, 15 (1994).

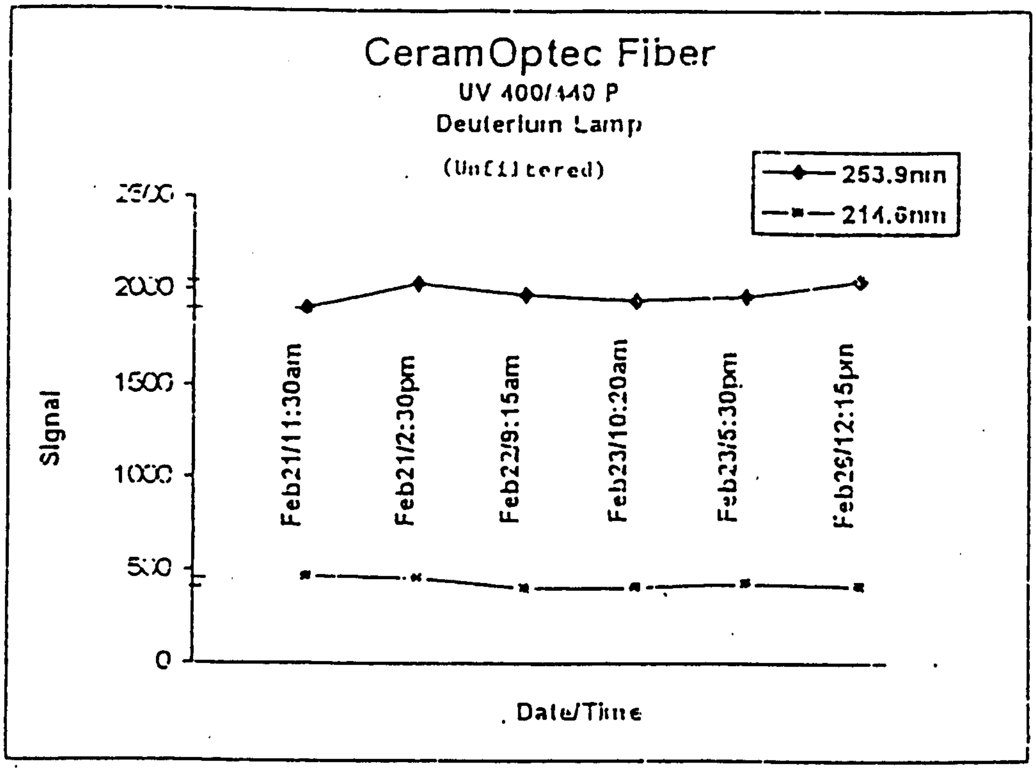

Figure 1: Exposure of UV400/440/465P fiber to an unfiltered Deuterium lamp for 5 days

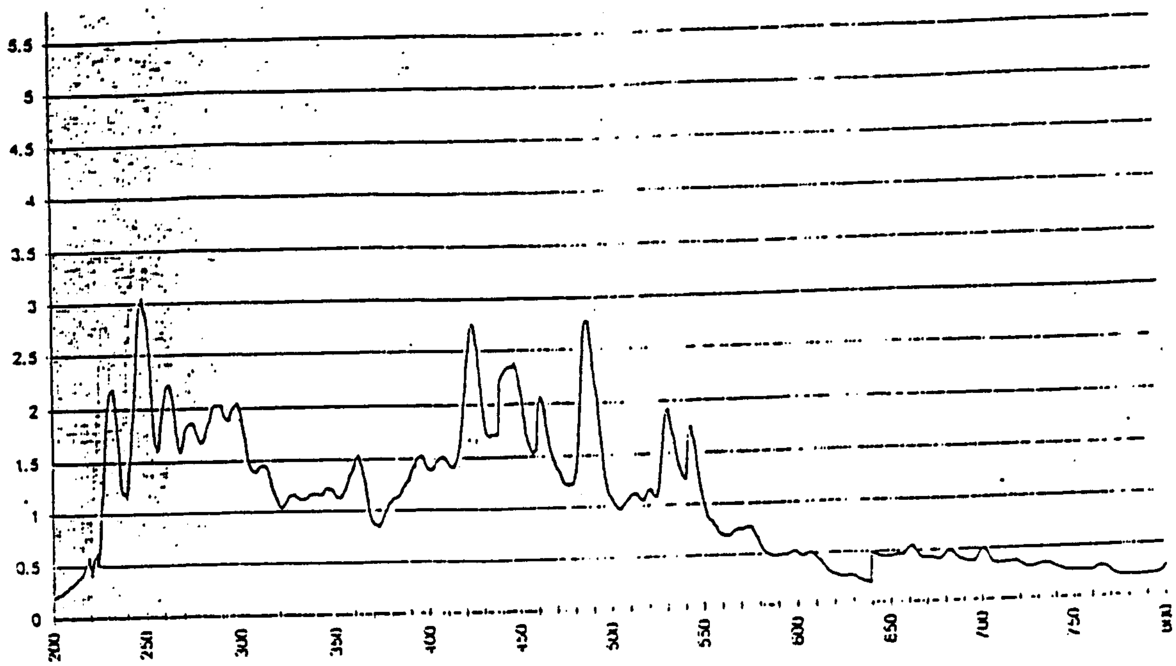

Figure 2: Spectrum of a high intensity UV source through standard optical fiber.

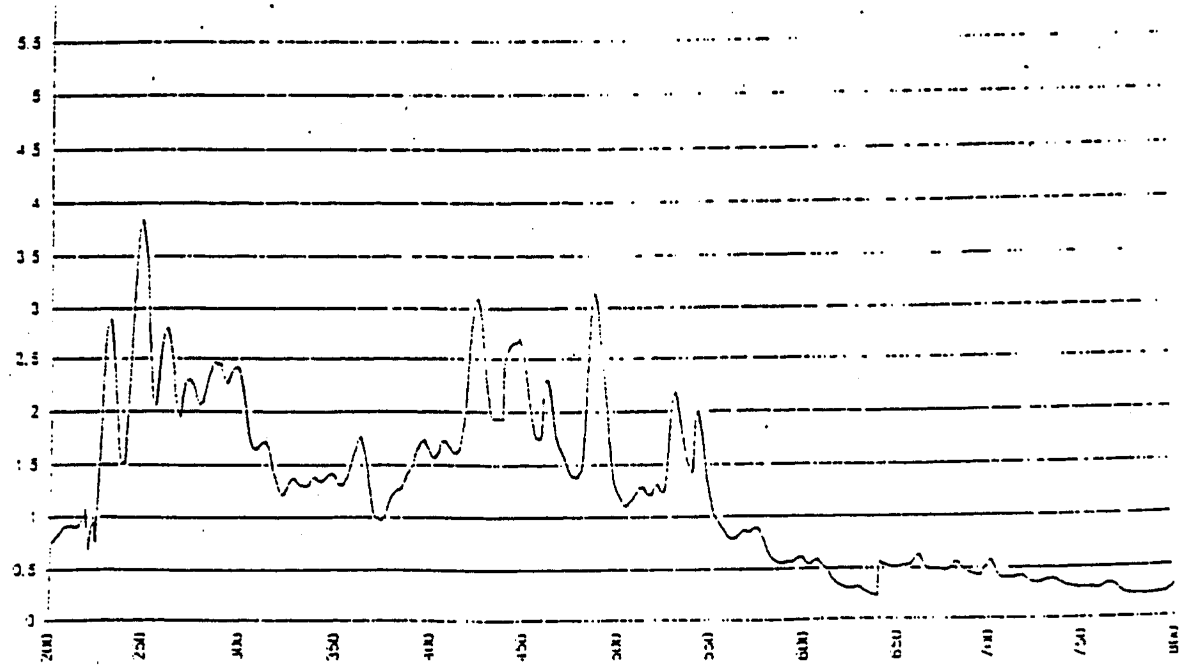

Figure 3: Spectrum of a high intensity UV source through Optran UV optical fiber.