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Final Technical Report:

Radiation Hardened Fiber Optics for Fusion Reactor Diagnostic Systems

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This final report comprises a brief synopsis of the following original papers published in refereed journals. For further details, these papers themselves should be consulted.

- (1) "Fast-neutron radiation effects in a silica-core optical fiber studied by a CCD-camera spectrometer," D.L. Griscom, M.E. Gingerich, E.J. Friebele, M. Putnam, and W. Unruh, *Appl. Optics* 33, 1022-1028 (1994).
- (2) "Radiation hardening of pure-silica-core optical fibers by ultra-high-dose γ -ray pre-irradiation," D.L. Griscom, *J. Appl. Phys.* 77, 5008-5013 (1995).
- (3) " γ -radiation resistance of aluminum-coated all-silica optical fibers fabricated using different types of silica in the core", D.L. Griscom, K.M. Golant, A.L. Tomashuk, D.V. Pavlov, and Yu.A. Tarabrin, *Appl. Phys. Lett.* 69, 322-324 (1996).
- (4) " γ and fission-reactor radiation effects on the visible-range transparency of aluminum-jacketed, all-silica optical fibers," D.L. Griscom, *J. Appl. Phys.* 80, 2142-2155 (1996).
- (5) "Visible/infra-red absorption study in fiber geometry of metastable defect states in high-purity fused silicas," D.L. Griscom, *Proc. 13th Int'l Conf. on Defects in Insulating Materials*, Wake Forest University, Winston-Salem, NC, July 1996.
- (6) "Influence of the cladding thickness on the evolution of the NBOHC band in optical fibers exposed to gamma radiations," O. Deparis, D.L. Griscom, P. Mégret, M. Decréton, and M. Blondel, *J. Non-Cryst. Solids* 216, 124-128 (1997).

Paper (1) describes an experiment wherein a suite of four different silica-based optical fibers was exposed to high-energy neutrons at the Los Alamos Spallation Neutron Facility and includes the description of a spectrometer based on a charge-coupled-device (CCD) camera specially assembled to register the visible-wavelength-range (~ 400 -700 nm) and near-infra-red (~ 700 -1000 nm) transmission spectra of four sample fibers and four reference fibers simultaneously. On the basis of this partially successful experiment, it was concluded that the F-doped-silica cladding glass was more resistant to fast-neutron damage than were the (high- OH) pure-silica-core materials; a germanium-

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doped-core fiber was decidedly inferior to all of the others. Paper (2) describes a follow-up study of the same four fiber types (all with acrylate plastic jackets) under ^{60}Co γ irradiation and reports an unexpected radiation hardening effect of ultrahigh-dose pre-irradiation. In this experiment, the same initially-induced absorption bands (one comprising a "tail" decreasing with increasing wavelength above 400 nm and the other a band or bands peaking near 600 nm) were observed to grow in the three pure-silica-core fibers. However, at doses of $\sim 1.5 \times 10^5$ Gy (note 1 Gy = 100 rad), these bands ceased to grow and at still higher doses they decreased in intensity exponentially with increasing dose, permanently disappearing at doses greater than about 10^7 Gy. This hardening effect (which was absent in the tested Ge-doped-silica-core fiber) was at the time attributed to an intrinsic mechanism involving light-assisted diffusion of displaced oxygen atoms which, according to the argument, react with pre-existing OH- and chloride-related defects thereby permanently eliminating them. However, as will be made clear below, this radiation hardening phenomenon must actually have resulted from a quite different (extrinsic) mechanism.

Paper (3) comprises an inter-laboratory comparison of the effects of γ irradiation on the optical absorption spectra of a different suite of four F-doped-silica-clad fibers with differently manufactured silica core materials (a high-OH silica, a low-OH/high-Cl silica, a low-OH/low-Cl silica, and an F-doped silica); in this experiment all fibers had *aluminum* jackets. The specific radiation hardening effect reported in (2) was *not* observed in any of these aluminum-jacketed fibers, causing the immediate rejection of the mechanism proposed above and prompting the alternative hypothesis that hydrogen atoms radiolytically released from the plastic jackets may have been responsible for the radiation-hardening effect reported in (2).

Paper (4) is a comprehensive report of the results of the γ irradiation of the four aluminum-jacketed fibers to a dose of 1.2×10^7 Gy (dose rate $\sim 1.9 \times 10^4$ Gy/h) briefly described in (3), as well as the results of a subsequent (mixed γ and neutron) fission-reactor irradiation to an added dose of 4×10^6 Gy (dose rate $\sim 2.5 \times 10^5$ Gy/h). The fission-reactor irradiation included a final fluence of > 2.8 -MeV neutrons $\sim 2 \times 10^{16}$ cm $^{-2}$. The high-chloride and high-OH fibers were the worst performers under γ irradiation, exhibiting losses $> 10,000$ dB/km below ~ 650 nm during irradiation and post-irradiation losses near 600 nm of 6,000 and $> 10,000$ dB/km, respectively. The low-OH/low-Cl and F-doped silica-core fibers were the superior performers at the highest γ -ray dose of 1.2×10^7 Gy. The low-OH/low-Cl-core fiber exhibited the lower loss (~ 2200 versus 3800 dB/km) at 600 nm, while the F-doped-silica-core fiber gave the lower loss (~ 500 versus 2200 dB/km) near 500 nm. In this context, it should be pointed out that the F-doped-core fiber was itself low in both OH and chloride and that the fluorine dopant appears to be benign (if not beneficial) with regard to radiation damage. However, at low doses, both of these low-OH/low-Cl fibers (including the F-doped one) initially exhibited unexpected gigantic bands peaking in wavelength near 670 nm and reaching maximum losses $\sim 30,000$ dB/km at doses $\sim 10^3$ - 10^4 Gy. Surprisingly, these longer-wavelength bands (but not the band "tail" nor the 600-nm band) in the aluminum-jacketed fibers were successfully radiation hardened by prolonged irradiation to doses greater than 10^7 Gy. These gigantic bands are judged to be endemic to pure-silica-core fibers with extremely low OH and chloride contents (< 5 and < 20 ppm, respectively). Moreover, the observed radiation hardening of these 670-nm bands must be the result of an intrinsic mechanism, as it is not possible for hydrogen to have penetrated the aluminum jackets of the test fibers. Paper (5) discusses some possible microscopic origins of this intrinsic radiation

hardening mechanism but concludes that more research is necessary to test the hypotheses set forth. Paper (6) provides additional evidence for the radiolytic-hydrogen mechanism as pertaining to the more potent radiation-hardening effect observed in plastic jacketed fibers.

In brief summary of the γ -irradiation results, it has become evident that the ability to harden silica-based optical fibers against γ -ray-induced absorption in the visible/IR spectral range as described in paper (2) was peculiar to plastic-jacketed fibers and is not reproducible in metal-jacketed fibers. Plastic-jacketed fibers are not practical for use in the environment of the International Thermonuclear Experimental Reactor (ITER) because the plastic would rapidly embrittle in the high radiation fields, compromising the mechanical integrity of the fibers. But, since the hardening mechanism was inferred to arise from in-diffusion of radiolytic hydrogen from the jacketing materials, one might hope to duplicate the effect in metal-jacketed fibers by fabricating them in such a way as to contain excess dissolved hydrogen molecules prior to irradiation. However, it may be a matter of practical difficulty to actually accomplish this. The present study of metal-jacketed, pure-silica-core fibers has shown the superiority of the low-OH/low-Cl-core materials (including F-doped-silica) under γ irradiation. It has shown also that the giant 670-nm bands initially induced in these low-OH/low-Cl materials are radiation hardened by an *intrinsic* mechanism (not requiring hydrogen) by pre-irradiation to doses $>10^7$ Gy. Unlike the 670-nm bands, the 600-nm bands continue to grow for doses above 10^7 Gy. However, based on the limited data available, this 600-nm absorption might be minimized by reducing the OH content substantially below 1 ppm by weight.

Notwithstanding the cautious optimism expressed above for the prospects of successfully hardening silica-based fibers against γ irradiation, the (limited) data in paper (4) pertaining fission-reactor irradiation raise serious concerns. Though providing only $\sim 1/3$ of the ionizing dose of the earlier γ irradiation, the reactor-irradiation gave rise to incremental losses at 600 nm and shorter wavelengths which were ~ 3 times greater than the γ -ray-only damage in both of the low-OH/low-Cl fibers (including the F-doped fiber). It is not yet possible to say whether this increased potency was due to the fluence of fast (>2.8 MeV) neutrons of $2 \times 10^{16} \text{ cm}^{-2}$ or to the twelve-times-higher ionizing dose rate (mostly γ). Moreover, the stable post-irradiation reactor-induced damage spectra of all four fibers were about the same within a factor of the order of 1.5. This means that with respect to reactor irradiations, it may not be possible to optimize fiber performance by optimizing the glass composition. For example, lowering OH and Cl contents no longer has the importance that it did in the case of γ irradiation alone (at least at a dose rate of 2×10^4 Gy/h). Certainly, if fiber optics are to be used for ITER diagnostic systems, more research will be required to develop methods of hardening them against the fluences of γ rays and 14-MeV neutrons which will accumulate to $\sim 10^{22} \text{ } \gamma/\text{cm}^2$ and $\sim 10^{22} \text{ n/cm}^2$ over the lifetime of the machine.

Reprints of papers (1) through (6) are attached to this report.

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