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Fiber optics in transient radiation fields*

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Fiber optics have been utilized in a variety of sensor and data transmission roles, some of which are complicated by the presence of ionizing radiation. In this paper, transient radiation effects in fibers are reviewed. The paper by E. J. Friebele¹ (in this same Conference) concentrates on longer term radiation effects, but includes selected transient effects data as well. Several literature reviews and conferences have covered related topics.²⁻⁵

Both luminescence and absorption processes are discussed in this paper, with emphasis on the latter subject. Most discussions are on effects occurring below 100 ns, with limited data in the microsecond time regime. This paper is intended as a review paper and its scope is restricted to previously published work. Areas that will profit from further study are highlighted.

Fiber luminescence

Both Cerenkov⁶ and fluorescence luminescence⁷ mechanisms have been identified in optical fibers. For these measurements, short lengths of optical fiber were irradiated with a pulsed e-beam accelerator (Febatron 705). The Cerenkov radiation was observed as a prompt light pulse that followed the time history of the pulsed e-beam. The Cerenkov origin was verified by studying the observed emission as a function of both optical wavelength and geometrical variables.⁸ In particular, the Cerenkov light can be emitted only at a specific angle relative to the electron beam determined by the electron velocity and the index of refraction of the fiber. The expected geometrical behavior was documented with emission peaking at a beam-fiber angle near 50 degrees. At a back angle of 170 degrees, emission was 0.007 of the peak emission. Wavelength dependence approximately tracked the λ^{-3} dependence anticipated for the Cerenkov light from 500 to 800 nm. The Cerenkov coupling efficiency was considered in several references.⁹⁻¹¹

While the Cerenkov radiation dominates prompt emission from high energy electron bombardment, slow emission components also exist. Low energy electron bombardment has been observed⁷ to produce slow fluorescence decay.

Fiber absorption

Radiation-induced transient attenuation has been studied at Los Alamos National Laboratory for more than seven years, and studies at the Naval Research Laboratory (NRL) have been conducted for considerably longer.¹² The Los Alamos measurements have all used variants of the experimental configuration shown in Figure 1. A pulsed light source, usually a Chromatix CMX-4 laser with an optical parametric oscillator, provides a pulse of light at an appropriate time relative to a pulsed e-beam accelerator (Febatron 705 or 706). The light is timed to be in a section of fiber undergoing e-beam irradiation. Both the injected light pulse and the same pulse after propagation through the dosed region are recorded on fast detectors and oscilloscopes. For some experiments, special temperature environments were used or detailed dosimetry was employed. Typical data traces are shown in Figure 2. Wavelengths from 600 to 850 nm have been used.

The NRL efforts¹² identified wide variations in radiation resistance of alternative compositions. Low-purity glasses, like lead silicate, were shown to have very severe transient absorption relative to high-purity fused silica. Germanium doped glasses demonstrated severe transient absorption, but very rapid recovery. Phosphorus doped fibers were noted to display less transient absorption upset, but required very long recovery times.

Microsecond pulse data

Early Los Alamos efforts used a Febatron 705 pulse providing a 20-30 ns FWHM burst of 2 MeV electrons. With this accelerator, the pulse persisted almost 100 ns. No data at times below about 100 ns were acquired. A general trend noted in this work, in agreement

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with NRL data, was that improved fiber purity was correlated to improved radiation resistance.⁹ The highest purity fiber, then available, was a plastic-clad-silica (PCS) fiber using a Suprasil I core¹³ produced by ITT as type P3-05-10 (or later as T3C3) fiber.

These same measurements were used to intercompare the NRL and Los Alamos measurement techniques using an identical fiber sample (shipped from NRL to Los Alamos). To accomplish this comparison, the Los Alamos measurements were extended to 2 μ s after the pulse and extrapolated to 10 μ s to correspond to the NRL data that extended from 10 μ s to longer times. Agreement was noted to within a factor of 2 with uncertainties in dose at both laboratories approaching the same factor.

Two other studies were completed with the Febetron 705, both using 600 nm wavelength. In one study, the ITT PCS fiber was pre-irradiated to determine if such pre-treatment could improve transient absorption as had been observed at 800 nm in long term studies at NRL.¹⁴ The Los Alamos data showed degraded performance in pre-irradiated fibers (although measurements were not made at the same wavelengths). Other measurements compared several bulk samples to the ITT PCS fiber. Bulk Suprasil I rods, with and without annealing, duplicated the ITT fiber performance while several other bulk samples (TOS silica, sapphire, and high purity quartz) were inferior.⁹ Thus fiber-draw conditions did not appear to degrade the bulk performance on this 100 ns time scale.

Nanosecond pulse data

A fast pulse e-beam accelerator (Febetron 706) has been used at Los Alamos for all recent studies. This accelerator produces a 1.0-1.5 ns pulse width after slow electrons are filtered from the beam. However, the low energy of this machine, 600 keV maximum, leads to a beam with poor penetration, nonuniform depth-dose profiles, and greatly complicated dosimetry even in very thin fibers. The original measurement series with this facility concentrated on developing an understanding of the fast transient behavior of the absorption.¹⁵ A series of measurements was made at two wavelengths (600 and 850 nm) and a wide range of temperatures under very high dose conditions. Typical data are shown in Figure 3.

An understanding of these data was attempted using a geminate recombination model¹⁶ in which the ion pair concentration, β , was assumed to be proportional to the transient absorption. This model uses

$$\beta = \beta_0 e^{\lambda t} \operatorname{erfc} \sqrt{\lambda t} \quad (1)$$

with λ , a recombination rate controlled by diffusion,

$$\lambda = \lambda_0 \exp(-\epsilon/kT) \quad (2)$$

Note that λ is highly temperature dependent. In Equation 2, ϵ is the barrier height for diffusion, k is the Boltzman constant, and T is temperature ($^{\circ}$ K).

The geminate model provided credible fits to the data at each wavelength for times beyond about 20 ns (cf. Figure 4). The geminate model response of Equation 1 was convolved with the Febetron pulse shape for this comparison. The recombination rates, λ , were independent of wavelength and displayed the anticipated temperature dependence (cf. Figure 5). From Figure 5, $\epsilon \approx 0.22$ eV, in reasonable agreement with measurements for other silicate glasses.

Geminate recombination theory did not fit the early time observations of transient absorption. The difference between observations and the geminate theory (cf. Figure 4) was observed to be approximately temperature independent, but did display wavelength dependence. A possible explanation for this component could be that a very high "effective" temperature prevails within a damage track that is not influenced by bulk material temperature.

After the temporal recovery model study, effort was focused on the dose dependence of absorption in several fibers, including the ITT PCS fiber¹⁷, and on improved dosimetry with the Febetron 706.¹⁸

Very little, if any, variation in transient absorption temporal recovery was noted over almost three decades of variation in dose. However, the peak observed absorption, when "normalized" by dose, displayed strongly nonlinear behavior (cf. Figure 6) at all wavelengths. One explanation for the observations of Figure 6 could be that a class of pre-existing defects is readily damaged at low dose, but that these pre-existing defects are saturated at higher doses.

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Further study investigated different fibers with particular emphasis on OH content. In general, high OH fibers (like the Suprasil 1 core fiber) exhibited superior radiation resistance for both long and short term measurements. Figure 7 shows a collection of data on different fiber types, including:

- a) High OH Raychem fibers (KSC and RSC PCS fibers, and VSC glass-on-glass fiber with fluorosilicate cladding);
- b) Fibres Optiques Industries all-glass fibers (a super-dry (SD) fiber with 30 ppm OH; a standard (STD) fiber with 200 ppm OH; and a high OH super-wet (SW) fiber with 1200 ppm OH); and
- c) An ultra-low OH fiber (3 ppm OH, type SM-100) from Dainichi-Nippon. The latter fiber was tested at NRL for long-term absorption¹⁹ and shipped to Los Alamos.

Two samples of Raychem VSC fiber were tested, one of which was provided by Lawrence Livermore National Laboratory. Figure 7 shows equivalent performance for several fibers for peak absorption per krad. In particular, the all-glass VSC fiber, the Raychem PCS fibers, and the ITT PCS were very similar. All low OH fibers are inferior except for the Dainichi-Nippon product. However, the transient recovery characteristics of the best fibers are compared in Figure 8 where the Dainichi-Nippon fiber is clearly inferior in recovery characteristics.

Areas for future study

Low OH silicas were believed to demonstrate poor transient radiation resistance until the recent Dainichi-Nippon performance (shown in Figures 7 and 8). The role of OH in radiation resistance is not fully understood, and the recent Dainichi-Nippon data offer real promise of future improvements with high purity, low OH silica materials. Low OH concentration is, of course, essential for any fiber used at long wavelength.

Very recent data¹⁸ have contrasted absorption induced with two very different electron sources -- the 600 keV Febatron 706 and a 22 MeV electron linac. Absorption induced with 22 MeV electrons appears to display very different, much slower, recovery than that observed with the low energy beam. Additional data, at different energies, are needed to define this trend, but this observation may reflect an increased dominance of lattice atom displacement phenomena under high-energy irradiation conditions. If this trend is confirmed in further measurements, extrapolation of induced absorption between alternative radiation sources will be greatly complicated. The fast pulse linac also offers the potential for better definition of the very early time (<20 ns) data where simple geminate recombination theory has not been sufficient to explain the observed transient absorption.

Very little data are available to define wavelength dependence of transient absorption. At 600, 800, and 850 nm the Los Alamos data are applicable and Lawrence Livermore National Laboratory personnel have recently constructed a system²⁰ to acquire data with continuous wavelength coverage from 500 to 800 nm. Above 850 nm, very little data exist.

Photobleaching has been extensively investigated for long-term effects, and large reductions in induced absorption have been noted under certain bleaching conditions.²¹ A few studies of photobleaching for very fast transient conditions have not shown measureable effects. Extrapolation of the long-term photobleaching data to short times (by demanding equal bleach energy delivered on short time scales) is also consistent with an absence of measureable effects for credible pulsed photobleach power densities. Nevertheless, photobleaching deserves additional study for transient environments and must become important for longer pulse lengths.

Alternative glass compositions need further study. All transient data suggest that high-purity silicas offer superior performance in radiation environments, but ultimate limits on purity and radiation resistance are not known.

Conclusion

The final goal for radiation damage studies should be a complete understanding of the various mechanisms contributing to transient absorption. Such understanding should serve to explain the early time phenomena, where geminate recombination theory does not follow the observations, as well as later phenomena extending to seconds and beyond. Without doubt, very different mechanisms must dominate the fiber performance at late times. While substantial progress toward this goal has been realized, much additional research will be required to attain the overall goal.

References

1. E. J. Friebele, this proceedings, SPIE Vol. 541.
2. E. J. Friebele, C. G. Askins, M. E. Gingerich, and K. J. Long, Nucl Instr and Meth B229 (1984) p. 355.
3. SPIE Vol. 506 (August 1984) ed R. Greenwell.
4. SPIE Vol. 404 (May 1983) ed D. Boucher.
5. SPIE Vol. 296 (August 1981) ed P. B. Lyons.
6. J. E. Golob, P. B. Lyons, and L. D. Looney, IEEE Trans Nuc Sci NS-24 (1977) p. 2164.
7. B. D. Evans and G. H. Sigel, Jr., IEEE Trans Nuc Sci NS-21 (1974) p. 113.
8. J. V. Jelley, Cerenkov Radiation and its Applications, Pergamon Press (New York, 1958).
9. P. B. Lyons, R. E. Kelly, and L. D. Looney, Proc Fiber Optics in the Nuclear Environment, ed R. C. Webb (Washington, 1980) Defense Nuclear Agency DNA 5308P-2, p. 83.
10. P. B. Lyons, L. D. Looney, J. E. Golob, R. Robichand, R. Seno, J. Madrid, L. Hocker, M. Nelson in Fiber Optics, ed by B. Bendow and S. S. Mitra (Plenum Press, New York, 1979) p. 379.
11. B. L. Pruett, R. T. Peterson, D. E. Smith, L. D. Looney, R. N. Shelton, Jr., SPIE Vol. 506 (1984) p. 10.
12. E. J. Friebele, Opt Eng 18 (1979) p. 552.
13. Suprasil I is a product of Heraeus-Amersil Corporation.
14. E. J. Friebele and M. E. Gingerich, J. non-Cryst. Solids 38 (1980) p. 245.
15. L. D. Looney, G. Turquet de Beauregard, P. B. Lyons, R. E. Kelly, SPIE Vol. 296 (1981) p. 17.
16. S. J. Rzad, P. P. Infelta, J. W. Warman, R. H. Shuler, J. Chem. Phys. 52 (1970), p. 3971.
17. P. B. Lyons and L. D. Looney, SPIE Vol. 404 (1983) p. 68.
18. A. A. Hopkins, R. E. Kelly, L. D. Looney, P. B. Lyons, SPIE Vol. 506 (1984) p. 209.
19. E. J. Friebele, M. E. Gingerich, K. J. Long, P. S. Levin, D. A. Pinnow, IEEE J. Lightwave Tech LT-1 (1983) p. 462.
20. M. D. Rotter, D. R. Jander, SPIE Vol. 506 (1984) p. 18.
21. E. J. Friebele and M. E. Gingerich, Appl Opt 20 (1981) p. 3448.

Figure 1. Experimental configuration for radiation-induced fiber optic transient absorption measurements. Three photodiodes provide: 1) a trigger to the e-beam accelerator, 2) a sample of the light pulse before exposure to the radiation, and 3) the light pulse after irradiation. Alternate geometries of fiber and accelerator are discussed in References 17 and 18. Dashed lines (----) refer to coaxial cables, solid lines (—) refer to fiber optics. The 200m PCS fiber serves to restrict the bandwidth of the input light pulse, resulting in a smoothly varying pulse. The 200m PCS fiber also provides delay to synchronize the Febetron output pulse with the optical probe. All oscilloscopes are Tektronix, Inc. (TEK) models.

Figure 2. Typical data traces for oscilloscopes of Figure 1. Data were acquired at 250 krad dose, 600 nm wavelength, for ITT T303 fiber. Note pronounced difference in transient absorption characteristics for different temperatures.

Figure 3. Measurements of transient absorption vs time for a range of temperatures. Note increased damage and very slow recovery at low temperatures. The pulse shape of the Febetron 706 is also plotted for comparison.

Figure 4. Comparison of transient absorption data of Figure 3 with the germinate recombination model of Equation 1. Only λ was adjusted for purposes of optimizing the fit.

Figure 5. Comparison of recombination rates, λ , for a range of temperature and wavelength values. Note that λ is not a function of wavelength. From Equation 2, this plot allows direct determination of both ϵ and λ_0 .

Figure 6. Peak transient absorption measured with experimental configurations like that of Figure 1. This peak absorption value depends on the dose rate, pulse shape, and recording system parameters, and will vary for alternative irradiation and/or recording systems. Observations with a single irradiation and recording system should be relatively comparable. Note the nonlinear behavior for doses below about 30 krad.

Figure 7. Peak transient absorption vs dose for 10 fiber types. The text provides more information on these fiber compositions. Note that all 10 fibers display the nonlinear performance of Figure 6 at low doses. Two different fibers of both VSC and RSC types were tested.

Figure 8. Transient absorption induced in 7 fibers for doses near 70 krad at 800 nm wavelength. Peak absorptions are normalized. Error bars reflect uncertainty in absorption for three attenuation levels. More uncertainty is involved in measurements of smaller absorption values, since smaller departures from pre-irradiation levels must be determined.