LA-UR - 84 - 2470

CONF - 840872 - - 20

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LA-UR--84-2470

DELL 016487

TITLE: TRANSIENT ATTENUATION IN OPTICAL FIBERS

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MASTER

**SUBMITTED TO SPIE's 28th Annual International Technical Symposium
Town and Country Hotel
San Diego, California**

August 19-24, 1984

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TRANSIENT ATTENUATION IN OPTICAL FIBERS

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Abstract

Low and high energy pulsed electron beams were used to generate radiation-induced transient attenuation in high-OH, Suprasil core, PCS fibers, demonstrating the energy dependence of the radiation damage and recovery mechanisms. A radiation resistant low-OH fiber was studied and its performance contrasted to that of high-OH material. Several fibers with differing core compositions were also studied.

Introduction

Many adverse environments in which fiber optics are playing critical data transmission roles involve ionizing radiation. Some applications require survival of fiber links in the presence of low dose rate exposures or long after (ms to days) an intense radiation burst. The work described here is motivated by our requirement that the fiber link transmit data during an intense radiation pulse. Major conferences have explored radiation effects on optical fibers for a wide variety of environmental parameters, and the proceedings for these events^{1,2,3} provide summaries of the worldwide interest in this topic.

At Los Alamos, we have concentrated on radiation effects at short times, less than 100 ns, after a very short radiation burst. Our previous papers^{4,5,7,10} explored such effects with low energy (< 600 keV) electron pulses on a variety of fibers. Our past data consistently showed superior performance for high-OH fibers, either plastic clad silica (PCS) or fluorosilicate clad silica. In the current work, we studied a very low-OH fluorosilicate clad fiber that had demonstrated superior performance at long times in Naval Research Laboratory studies⁶. We also extended our previous studies of high-OH PCS fiber to lower doses and confirmed trends in previous data. In addition, a series of ten experimental fibers were surveyed for radiation sensitivity to a low dose pulsed electron beam, and major improvements were made in our pulsed electron beam dosimetry.

Limited data are also presented using an alternative radiation source that delivered monoenergetic 22 MeV electrons at low dose. The transient recovery induced by this high energy electron beam is very different from our low energy electron data, indicating that the physical processes dominating the transient attenuation recovery depend strongly on electron energy.

Experimental Method

Two sources of pulsed irradiation were used. A Febetron 706 was used to provide a 1.5 ns pulse of electrons of maximum energy 600 keV. A Linac at EG&G, Inc., Santa Barbara Operations, was used to provide a 50 ps pulse of monoenergetic electrons at 22 MeV. The Linac was used to explore the energy dependence of short term radiation recovery.

Fibers tested

Because it is well characterized^{8,9,11}, ITT PCS T303, with 125 μ m Suprasil core and 500 μ m overall diameter, was used as a standard against which other fibers were compared. New data on ITT PCS were also obtained. Ultra-low-OH fibers, manufactured by Dainichi-Nippon, were obtained from the Naval Research Laboratory. A series of experimental fibers were obtained from Heraeus-Amersil with varying core compositions. Some data herein are compared to previous studies that included fibers from Raychem and Fibres Optiques Industries.

Febetron experiments

The Febetron 706 was used to provide a 1.5 ns electron pulse that irradiated a coil of the fiber under test. The electron beam was scattered by a thin Al foil at the exit of the Febetron to provide a more uniform irradiation over the coil area. The fiber coil (length 10 - 50 cm) encircled a collimating aperture, behind which was a fast Faraday cup. The electron pulse was recorded on every Febetron pulse as a measure of relative dose.

Biplanar vacuum photodiodes (ITT 4014 or FW114 A) detected the light signal before and after the dosed region. The unirradiated signal was derived from mode stripped light out of a coil of ITT PCS fiber. We note in passing that apparently different attenuation recovery shapes have been seen with different detector types, particularly when solid state PIN detectors were used. Several solid state detectors showed no recovery of radiation-induced attenuation for hundreds of nanoseconds. Although these detectors were optimized for fast (GHz) response, they appeared to saturate on the long laser pulse and to have a long tail which altered the apparent recovery curve. One faulty biplanar vacuum photodiode altered the observed recovery curve, apparently due to ion feedback in a gaseous diode. Photodiodes used for these measurements were tested and did not exhibit this abnormal response.

Signals were recorded on Tektronix 7104 and 7844 oscilloscopes. The system is shown schematically in Figs. 1 and 2. Data were recorded on Polaroid film for subsequent analysis.

Fig. 1 (left). Block diagram of the experimental setup at the Febetron. The signal channel is also input to a fast Tek 7104 oscilloscope.

Fig. 2 (above). Geometry of the experimental setup at the output of the Febetron.

Relative dosimetry was provided by the Faraday cup. This cup output was related to dose by comparison to radiachromic film (Far West Technology, Inc., Goleta, CA). This film provided a low mass ($\sim 5 \text{ mg/cm}^2$) monitor of dose. Calibration of the film with a ^{60}Co source confirmed the vendor's sensitivity data.

The low electron energy (maximum 600 keV) of the Febetron 706 leads to concern about non-uniform dose within the fiber. This was tested by preparing a multilayer stack of the thin radiachromic films and thin Al foils. This stack was then exposed to multiple Febetron shots while the Faraday cup current was recorded. The resulting data sets (Figs. 3 and 4) established conversions from observed current to dose in the fiber core. An approximate dose according to the Faraday cup was calculated by assuming that energy loss to the fiber core could be modeled by the electron stopping power for SiO_2 at 300 keV energy. The Faraday cup correction factor for each film layer is the ratio of the dose recorded by the radiachromic film to the dose according to the Faraday cup. The approximate dose in a fiber core is determined by multiplying the dose according to the Faraday cup monitor pulse by the average Faraday cup correction factor over the core of the fiber.

Fig. 3. Comparison of Faraday cup correction factor depth profiles for original and reentrant Faraday cups.

Fig. 4. Comparison of Faraday cup correction factor depth profiles for the reentrant Faraday cup before and after the Heraeus-Amersil experimental series. This illustrates the degradation in average electron energy during that series.

In previous measurements^{4,6,7}, Faraday cup correction factors were close to 4, probably due to scattering and subsequent loss of low energy electrons by the collector. The geometry of the original cup (Fig. 5) permitted a great majority of the electrons entering the cup to escape collection. To improve the sensitivity of the cup a reentrant modification was made to the original cup (Fig. 6). Correction factors were 1 - 1.5 with the reentrant Faraday cup (Fig. 3).

Fig. 5. Geometry of original Faraday cup.

Fig. 6. Geometry of reentrant modification to Faraday cup.

During measurement of the 10 Heraeus-Amersil experimental fibers, the amplitude and energy of Febatron pulses decreased considerably. The dose range decreased from 10 - 20 kRad at the beginning of the series to 3 - 6 kRad at the end. The dose profiles before and after measurement of the Heraeus fiber are shown in Fig. 4, and suggest that the Febatron energy was severely degraded during this test series since the electron range in the material appeared to have decreased.

the Faraday cup correction factor changed significantly, and dose uncertainty for those fibers is substantially larger.

Linac experiments

Radiation induced transient absorption in optical fibers has been measured previously with the EG&G, Inc. Linac⁸. At that time dose was limited to ≤ 500 Rad. Recent major improvements to the Linac now allow doses up to a few kRad, overlapping the low dose range of the Febetron. The Linac provided a 40 - 50 ps pulse with ~ 9 nanocoulombs of 22 MeV electrons per pulse. The test fiber was irradiated at a grazing angle over a 43 cm length in a diverging beam of radius 0.31 cm where the fiber was closest to the output port and 1.0 cm where the fiber was farthest from the port. Because the beam was diverging, the dose delivered to the fiber closest to the port was approximately 10 times higher than that delivered farthest from the port.

A Xenon flashlamp provided a broad band light source which was filtered with a 50 nm wide bandpass filter centered at 600 nm. A biplanar vacuum photodiode (ITT 4014) detected the light signal after the dosed region. The output of the photodiode was amplified with a Comlinear 1 GHz amplifier. The photodiode, amplifier and amplifier power supply were located in an RF-shielded enclosure inside the Linac radiation cell. Signals were transmitted from the radiation cell to a Tektronix 7104 oscilloscope on 30 m of high bandwidth Foamflex cable. The system is shown schematically in Fig. 7.

Fig. 7. Block diagram of the experimental setup at the EG&G/SBO Linac. Note the test fiber is irradiated at a grazing angle to the electron beam.

The dose absorbed by the fiber was determined by measuring the average beam current per pulse and the radius of the beam at both ends of the fiber. Assuming the beam diverged uniformly, the charge density was expressed as a function of position along the fiber. This function was integrated over the length of the fiber, multiplied by the appropriate electron stopping power, and finally divided by the length of exposed fiber to give an average dose to the fiber of 1.6 kRad.

This calculation, however, should be treated only as an upper limit to dose. Several factors may lower the actual dose significantly. The stopping power⁹ used in the calculation included only ionization loss. Bremsstrahlung is not locally deposited at these energies and should be excluded in this calculation. However, for these small fiber diameters (480 μ m with 120 μ m core) a significant fraction of the ionization electron energy will escape deposition in the fiber core and should also be excluded. Furthermore, the fiber angle in the beam is not known and self-shielding of the fiber length is probable. These factors may lead to substantially lower actual dose than the calculated value.

Experimental Data and Discussions

Data at 600 nm were obtained comparing the recovery curves of ITT PCS T303 irradiated by electrons of different energies. All other data were acquired at 800 nm. The data on ITT PCS were extended to low doses. In addition, 10 experimental fibers from Heraeus-Amersil of varying chlorine and OH concentrations were examined at low doses (3 - 20 kRad). At higher doses (30 - 150 kRad) two fibers, Dainichi-Nippon and Raychem VSC, were compared to previously measured fibers.

ITT PCS

Data at 600 nm were obtained at the EG&G, Inc., Santa Barbara Linac and are plotted in Fig. 8 with Febetron data from previous work*. These data do not show the fast component of the short term transient absorption previously observed at lower electron energies and dose rates. In addition to lacking the fast component of the recovery, the Linac data recovers considerably more slowly over tens of nanoseconds. It should be noted that the dose rate at the Linac is approximately 30 times higher than that at the Febetron for the same dose because of the short pulse width available at the Linac. However, in Ref. 4, Febetron data for doses up to 700 kRad were shown to exhibit fast recovery characteristics similar to the 1.4 kRad data of Fig. 8. These high dose Febetron data represented dose rates well above that of the Linac data. The difference between the Linac and Febetron recovery curves is probably due to the energy dependence of the damage and subsequent recovery mechanisms, but may also be influenced by dose rate variations. At low electron energy, the energy transfer mechanism is dominated by ionization. As electron energy increases, displacement of silicon and oxygen atoms becomes more important. The threshold energy for such displacement is ~ 160 keV for oxygen and ~ 260 keV for silicon. Atomic displacement and consequent diffusion of heavy atomic species for recovery is relatively slow compared to electron diffusion.

Fig. 8. Comparison of transient attenuation recovery curves resulting from irradiation at high electron energy (Linac, 22 MeV) and low electron energy (Febetron, < 600 keV). Dose for each curve was ≤ 1.6 kRad for the Linac data and ~ 1.4 kRad for the Febetron data.

The data at 800 nm have been extended to low doses (1 - 3 kRad). These data confirm the trend observed previously* that the peak damage per unit dose increases rapidly as the dose decreases below 40 kRad (Fig. 9). In past papers, we speculated that the behavior shown in Fig. 9 indicates saturation of a particular class of defects above a certain threshold dose (~ 60 kRad), with other defects proportional to dose dominating the high dose damage. Because the absolute damage in PCS T303 fiber was very small at these low doses, long lengths of fiber (50 - 80 cm) were exposed to obtain measurable damage. Transit time through the fiber was then 2 - 3 times that for previous measurements, effectively degrading the peak response for these low dose measurements. Thus the actual peak damage may have been still higher, and the relative increase in peak damage per unit dose with decreasing dose may be even more dramatic than is shown in Fig. 9. As we noted earlier, the difference in the dose profiles in Fig. 4, before and after the Heraeus fibers, suggests a decrease in electron energy as the Febetron degraded to the low dose regime. Since the low dose ITT T303 data was taken after the degradation to low dose, the energy dependence of the peak damage may also be involved.

Other fibers

A second sample of the Raychem VSC fiber was provided by the Lawrence Livermore National Laboratory. This sample is denoted as LLNL VSC in Figs. 10 and 11. In Ref. 4, we noted that Raychem VSC fluorosilicate clad silica fiber was the first all glass fiber tested at Los Alamos to equal the radiation resistance of ITT PCS with Suprasil core. The peak damage per unit dose of the LLNL sample appears to be slightly less than that of the previous sample (Fig. 10), but the difference is well within measurement statistics. The recovery of the LLNL sample is also within statistics of the previous sample.

The Dainichi-Nippon fiber (SM-100 S) provided by the Naval Research Lab, had been identified as a low-OH fiber that outperformed high-OH fibers on long time scales (minutes)⁵. Past measurements have shown optimal performance from high purity, high-OH, plastic clad silica fibers. Within measurement statistics, the peak damage per unit dose (Fig. 10) appears comparable to Raychem KSC fiber and not much worse than the Raychem VSC and ITT T303, but the recovery of the Dainichi-Nippon fiber is considerably slower than these fibers, as shown in Figs. 11 and 12.

Fig. 10 (above). Peak transient attenuation for ten types of fiber, four PCS fibers and six all glass fibers. Data points shown represent the results of multiple Febetron 706 tests.

Fig. 11 (right). A figure of merit for transient attenuation recovery is plotted here for the ten fibers of Fig. 10. The data symbols for each fiber are identical to those of Fig. 10.

The ratio of peak attenuation to the attenuation 60 ns after the peak may be taken as a figure of merit for the short-term recovery of a fiber. In Fig. 11, the figure of merit is plotted at several doses for a variety of fibers from Ref. 4, as well as the Dainichi-Nippon fiber. (The error bars shown at 10 and 50 kRad apply to all measurements at those doses. The error at 10 kRad reflects the difficulty of reading relatively small damage at 60 ns at

Fig. 12. Transient attenuation for the five hardest fibers of Fig. 9 and the Dainichi-Nippon fiber. Similar doses are used and the peaks are normalized to a common value.

Heraeus-Amersil experimental fibers

Ten fibers of varying chlorine and OH concentrations were provided by Heraeus-Amersil for evaluation. Because the Febetron degradation took place during these measurements, the doses involved are low (6 - 20 kRad). The Faraday cup correction factor was increasing during these measurements, but was known both before and after the measurements. To determine the Faraday cup correction factor for each fiber tested, the average integral of the Faraday cup pulses for that fiber was compared to the average integral before and after the Heraeus series, and the Faraday cup factor was interpolated from these known values.

These data confirmed previous observations that high-OH fibers show faster recovery than low-OH fibers¹⁰. But, while the advantages of high-OH extend to long time scales (minutes)¹¹, the long term disadvantages of high chlorine do not appear significant on short time scales (nanoseconds). It has been observed on long time scales that chlorine treated samples show poor recovery^{8,12}. Short term measurements did not show evidence of such an effect, but delays in the chlorine analysis of 4 of the experimental fibers prevent us from making a statistically merited conclusion on the effect of chlorine at this time. Data available indicate some dependence on the ratio of chlorine concentration to OH concentration. The peak damage per unit dose decreases dramatically as the Cl/OH ratio drops below 1, and the recovery figure of merit also shows slight improvement for low-Cl/OH fibers. A summary of the data obtained is shown in Table 1.

Table 1. Heraeus experimental fibers*

Sample Number	Atten. Before Test at 800 nm dB/km	Concentration (ppm)		Average peak damage (dB/m-kRad)	Recovery Figure of Merit	Average Dose (kRad)
		OH	Cl			
1	4.0	3.0	50	0.94	1.2	7.0
2	3.0	8.3	225	0.69	1.6	14
3	4.2	1730	370	0.40	3.2	15
4	6.1	1280	455	0.40	2.0	4.6
5	3.6	0.6	1400	0.66	1.4	16
6	4.8	500	-?-	0.43	1.5	5.7
7	4.2	1.4	-?-	1.1	1.3	12
8	5.2	1170	175	0.77	1.9	11

Conclusions

The transient recovery mechanism for pure silica fibers on a short time scale was shown to be dependent on the energy of the incident electrons. This has substantial implications for extrapolations of damage data between different radiation environments. The peak damage per unit dose for ITT PCS increased rapidly as the dose decreased, but appears constant above a certain threshold (~ 60 kRad). High-OH fibers recovered faster than low-OH fibers. Chlorine concentration did not appear to have a significant effect on the short term recovery characteristics. The fast transient recovery characteristics of Raychem VSC fluorosilicate clad silica fiber were confirmed. The Dainichi-Nippon low-OH fiber, which out performed some high-OH fibers on long time scales, showed a peak damage comparable to that of the best high-OH fibers, but recovered much more slowly than high-OH fibers.

Acknowledgments

The authors wish to thank the Fiber Optics group at EG&G/LVO and NTS for continuing technical support especially L. Tabaka, R. Schiltz, V. Romero, and E. Popc. We also wish to thank P. Zagarino, S. Lutz, C. Ashford and the Linac operators of EG&G/SBO for their work on the Linac data; and G. Sigel of NRL, and F. Roeske of LLNL, for providing fiber samples.

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