Contributed Papers
Abstract

Bremsstrahlung and electron-beam radiation experiments have been performed to measure transient radiation darkening and recovery at room temperature in seven commercial optical glass fibers. Several of these fibers were also tested at temperatures approaching the temperature of dry ice, 216 K. Fiber responses measured during and immediately after the radiation pulse have been reduced to delta function response parameters using curve fitting techniques. Most fibers examined demonstrated a complex recovery history that suggests the presence of multiple annihilation mechanisms with significantly different characteristic times. At room temperature, pink darkening coefficients ranged from $10^{-3}$ to $10^{-5}$ dB/m-R; typical recovery rates ranged from $10^4$ to $10^5$ s$^{-1}$. At temperatures between 216 and 247 K, most fibers demonstrated increased darkening and markedly slowed recovery rates, although exceptions to this result were observed.

Introduction

An optical fiber waveguide exposed to a fast pulse of ionizing radiation experiences a transient optical darkening that can be very much greater than the permanent darkening produced by the same pulse. The amplitude and time history of the transient effect appears to depend only on the radiation dose and time history, the fiber temperature, and the fiber composition. There are applications for fiber optics (e.g., in nuclear radiation effects tests and nuclear diagnostics tests) where transient darkening is a serious concern in the time interval of 0 to 500 ns, measured from the beginning of the radiation pulse. This paper describes an experiment performed to characterize early-time darkening in a number of commercially available fibers. An Ion Physics FX 45 Flash X-ray machine, operating initially in the bremsstrahlung mode, and later in the electron-beam mode, was used to obtain pulsed ionization doses in the test samples, all of which were glass-core fibers. Three ITT fibers were examined: the step-index T103 and T303 (PCS fibers), and the graded-index T223. Four Corning fibers were also tested: the step-index short-distance fiber (SD), and the graded-index IVPO, OVP0, and double-window fiber (DW). All fibers were exposed at room temperature, 295 K, and in addition, the IVPO, OVP0, DW, T223, and T303 fibers were also exposed at temperatures approaching the temperature of dry ice, 216 K. The measured data have been reduced to empirical response parameters that are independent of sample length and the radiation dose time history.

Experimental Configuration

Fig. 1 shows the nominal configuration of the apparatus used to measure the transient radiation response of optical fibers. Test samples were non-cabled fibers carrying the manufacturer's standard protective coatings, all of which were "thin" to the radiations used in the experiment. Two provisions were made for circumventing the optical interference expected during the radiation pulse: 1) interference filters with passbands of 20 nm FWHM centered on the laser wavelength (800 nm) were interposed between the output ends of the test fibers and the avalanche photo-diodes (APDs) in the receiver, thus blocking most of the Cerenkov light, and 2) a high frequency sine-wave modulation of the laser signal was used to provide a direct means of tracking the darkening of the fiber through and beyond the radiation pulse.

In the electron-beam experiments, the five fibers were cooled by the simple expedient of holding a cylindrical block of dry ice in forced contact with the rear surface of the fiber holder. The front surface of this aluminum piece was provided with a shallow fiber groove (20 cm circumference), six small indentations inside and outside the groove circle for implantation of bare thermoluminescent dosimeters (TLDs), and a space for mounting an iron-constantin thermocouple junction in direct contact with the metal surface near the fiber.

During the bremsstrahlung tests, several half-kiloventen exposures of a given fiber segment were made to compile a complete response history. This was possible because the radiation pulses were very reproducible, and the prior dose history had no apparent affect on the transient response of the sample, the first 120 ns of which was recorded on every shot. Moreover, no cumulative permanent darkening after several exposures was observed. During the electron-beam tests, however, the radiation fluence per shot was in the range of 40-60 kR, and permanent darkening was not negligible. For this reason, a fresh fiber segment was advanced into the holder for each electron-beam exposure. In both bremsstrahlung and electron-beam phases of the experiment, TLDs were routinely removed for readout after each radiation pulse. The TLDs used were CaF:Mn dosimeters; they were read out in equipment calibrated to yield radiation fluence rather than dose. Conversion of fluence to dose in the fibers requires a quantitative specification of the fiber core compositions, information generally unavailable because of its proprietary nature. For this reason, the radiation environments are quantified below in terms of fluence (roentgens, R) and energy spectrum rather than dose in rads, even though the latter is more fundamental to the darkening effect. Similarly, the results of the experiment are reported in terms of fluence.

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+ Harry Diamond Laboratories
++ Defense Nuclear Agency, Washington, D.C.
The Ion Physics FX 45 radiation source was charged to 4.1 MV. The machine’s bremsstrahlung pulse shape (20 ns FWHM) was measured with an ionization chamber located in the test volume and is given in fig. 2. The photon fluences measured with TLDs at the sample location ranged from 0.4 to 0.7 kR. The photon energy distribution is given in fig. 3.5 In the electron-beam phase of the experiment, the FX 45 was first operated in its standard mode, producing a nominal 45-kR fluence at the fiber location. The waveform of this radiation pulse is given in fig. 4 and has a pulse width of 18 ns (FWHM). It was measured with a current sensor located in the diode space of the machine and shows evidence of a cavity ring at late time, which should not be considered a part of the electron output. The electron energy spectrum for this pulse is given in fig. 5.6 The FX 45 was then operated in a crowbarred mode, which shortens the pulse to 12 ns (FWHM) as shown in fig. 6 and provides the electron energy spectrum given in fig. 7.6 The radiation fluence at the fiber obtained in this case was approximately 55 kR.

Fig. 8 shows a typical fiber response. It was displayed on a dual-beam Tek 7844 oscilloscope and photographed using fast Polaroid film. The procedure followed throughout the experiment was to synchronize oscilloscope sweeps to the machine discharge.
in such a way that the earliest part of the trace recorded on the shot film gives the preradiation amplitude of the transmitted sine-wave, followed directly by the portion of the sine wave signal that shows the effects of radiation darkening of the fiber. In this way, unequivocal attenuation ratios can be drawn from each shot record, with no concern for gain drift in the system from one shot to the next. The dynamic range of measurements made on both dual beam and single beam oscilloscopes is approximately 20 dB. This is less than what might otherwise be expected because oscilloscope preamp gains had to be reduced to accommodate the APD's voltage shift at zero time; this effect, due to the sudden reduction of light intensity at the receiver caused by fiber darkening, is apparent in fig. 8.

Data Reduction

A quantitative theoretical model explaining radiation-induced transient darkening in fiber glasses has not been established in the literature. For this reason, an empirical approach to data reduction was chosen for this experiment. Its objective was to extract differential attenuation parameters from the raw data. In this way, the integrations of finite sample length and radiation pulse length on the measured result could be stripped away, leaving quantities that more directly reflect the fundamental radiation response of the glass. To obtain these parameters from the raw data, the following sequence was followed: (1) an empirical model was chosen for the intrinsic response of the glass to a finite radiation fluence delivered in an infinitely short pulse, (2) this expression was then convolved over the length of the fiber sample, (3) the length convolution was then folded over the normalized radiation time history, (4) the double convolution was compared to the measured attenuation history, and (5) the model parameters were adjusted and the procedure was repeated until a satisfactory curve fit was obtained. The following paragraphs describe how these steps were carried out.

After an inspection of data produced during the bremsstrahlung phase, an empirical model was selected with the form \( \left[ 1-a_0 e^{-k_0 \Delta t} \right] \left[ 1-a_1 e^{-k_1 \Delta t} \right] \). The subscripts refer to what appear to be two separable components in the observed fiber recoveries, each component characterized by its own recovery time constant. The convolution of this expression over the length of the fiber sample was accomplished according to the expressions

\[
T(t_j) = \sum_{k=1}^{j} \left[ 1-a_0 e^{-k_0 \Delta t} \right] \left[ 1-a_1 e^{-k_1 \Delta t} \right].
\]

for \( 0 < j < t_L/\Delta t \),

\[
T(t_j) = \sum_{k=j}^{j} \left[ 1-a_0 e^{-k_0 \Delta t} \right] \left[ 1-a_1 e^{-k_1 \Delta t} \right],
\]

for \( j > t_L/\Delta t \),

and

\[
T(t_j) = 1 \quad \text{for } t_j < 0,
\]

where \( t_j = j \Delta t \) is the time variable measured from the initial appearance of radiation-induced attenuation on the data record; \( \Delta t \) is the time step selected for the computation; \( T(t_j) \) is the attenuation factor of the sine-wave signal at time \( t_j \); \( L \) is the length of the fiber sample that has received an instantaneous radiation fluence \( D(t) \); \( T \) is the time required for light to traverse the fiber segment; the empirical constants \( a_0, a_1, k_0, k_1 \) represent the component recovery processes; and the product operator \( \pi \) provides for the progressive attenuation of the light signal as it travels through the fiber.

The next step was to convolve \( T \) over the normalized radiation time history \( f(t') \):

\[
A(t) = \int_0^\infty T(t-t') \cdot f(t') \, dt',
\]

where \( A(t) \) is now the amplitude modulation of the signal after its transmission through a length \( L \) of the fiber, which has received a total fluence \( D \) during the time interval of the radiation pulse. This calculated modulation history is then compared with the measured result, and the \( a \)'s and \( k \)'s are adjusted until a suitable curve fit is obtained. The final values for the \( a \)'s depend on the total radiation fluence \( D \); this dependence is removed by transforming the \( a \)'s into the desired differential parameters according to the expression:

\[
A_\lambda = \left( P/D \right) 10 \log \left( 1-a_\lambda \right) dB/m-R,
\]

where \( A_\lambda \) is in units of dB/m-R, and \( P \) is the number of \( \Delta t \) time steps required for light to traverse a unit length (1 m) of fiber. The \( \lambda \)'s are given in units of s\(^{-1}\).

Experimental Results

Graphical comparisons between experimental measurements and their corresponding curve fits are given in figs. 9 through 19. The response parameters used to achieve these curve fits are listed in the table along with the relevant experimental parameters.

Figs. 9 and 10 show the results of convolving response parameters obtained from curve fits of data from 4 m lengths of T103 and T223 fibers, respectively, over 20 m lengths of the same fibers. The data in these figures were obtained in low-fluence x-ray exposures at room temperature. Also shown for comparison are curve fits obtained directly for the 20 m data. The parameters obtained from the short-length measurements produce moderately successful curve fits when convolved over the longer fiber lengths, although the late-time agreement for T223 is not as close as that obtained for T103. The differences between the parameters obtained from the 4 m data and the corresponding parameters obtained from the 20 m data are close to the estimated curve fit uncertainties given in the table.
Figs. 11 and 12 are curve-fit comparisons for the SD and T103 fibers, respectively. These data were obtained at room temperature during high-fluence electron-beam exposures of fibers 20 cm long. There is a 20-30% agreement in the time constants and a factor of three agreement in the attenuation constants obtained for the T103 fiber in the low-fluence bremsstrahlung and high-fluence electron-beam experiments. The SD fiber was one of the two slowest fibers tested at room temperature and showed an unexplained "knee" 30 ms into its recovery following exposure to the electron-beam pulse.

The remaining figures also pertain to the electron-beam experiment and show not only comparisons between room temperature measurements and their curve fits for IVPO, OVPO, DW, T223 and T303 fibers, but also similar comparisons for data obtained when these fibers were cooled with dry ice.
Figs. 13 and 14 give the T223 responses in the early- and late-time regimes, respectively. The effect of cooling the fiber 70 K is pronounced in both figures. The early portion of the curve fit in fig. 13 was obtained by selecting an artificially small time step for the convolution calculation, 0.2 ns. An interesting aspect of the experimental data shown in fig. 14 is that once the cooled fiber began to transmit a measurable signal (at 0.5 s), its recovery rate was very close to the initial recovery rate of the room-temperature fiber.

Fig. 15 Early responses of IVPO fiber to electron beam

Fig. 16 Late responses of IVPO fiber to electron beam

Very similar results obtained with the Corning IVPO fiber are shown in figs. 15 and 16. Fig. 17 shows transient darkening in the OVPO fiber. Like the short-distance fiber, it is very slow to recover at room temperature and shows an even slower recovery at 235 K. The cold-temperature response for this fiber was unusual in that a measurable signal was transmitted during and after the radiation pulse, but its amplitude did not change noticeably until almost a second after the pulse. The empirical model described earlier, \((1-ae^{-rt})\), does not reproduce the shape of this response; for illustrative purposes a single-component recovery curve is given in the figure and its parameter values are listed in the table.

Fig. 17 Responses of OVPO fiber to electron beam

Fig. 18 Early responses of double window fiber to electron beam

Fig. 18 shows results for the Corning double-window fiber. A special set of circumstances existed during characterizations of this fiber. The room-temperature measurement was completed first, and a new fiber segment was advanced into the fiber holder for the cold-temperature measurement. After the sample temperature was stabilized at 247 K and the FX 45 was fired, it was determined that equipment failure had caused the loss of the first 100 ns of response data.
The slow sweep record (500 ns/div) provided response data after 100 ns, which is plotted as solid dots in fig. 18, eight and a half minutes later, a second radiation pulse was applied to the same cooled fiber segment and the same set of TLDs that were exposed in the preceding shot (the fluence given in fig. 18 is half of the two shot TLD readout). The open asterisks show the attenuation history measured during this second shot, normalized to the signal amplitude observed just nanoseconds before the arrival of the second pulse of radiation. At that moment, the fiber showed residual darkening from the first exposure. It should be in that the signal amplitude prior to the second pulse was 75% of the value measured before the first exposure. A calibration carried out several seconds after the second shot showed that the signal had dropped another 2% to 73%. The transient responses measured on the two cold-temperature irradiations are in good agreement with each other, but, unlike the cold-temperature responses observed in the other fibers, appear smaller in amplitude than the room-temperature response.

![Figure 19 Early responses of T-303 fiber to electron fiber](image)

Fig. 19 Early responses of T-303 fiber to electron fiber

Fig. 19 presents an early-time comparison for the T303 fiber. The time history of the transient darkening measured at 237 K is qualitatively very similar to the room-temperature result, but the darkening amplitude is greater. Not unexpectedly, this low-bandwidth pure-glass-core fiber showed less sensitivity to radiation than the other fibers tested, all of which contained one or more dopants.

The uncertainty bars in the figures discussed above are estimates based on the trace resolution on the film, the random noise fluctuations in the laser output, and the slope of the baseline signal. In general, the largest measurement uncertainty belonged to the portion of the data trace containing the avalanche photodiode's voltage shift and the Cerenkov noise pulse. The response parameters used to curve fit the measurements are listed in the table. Each entry carries a superscript indicating the estimated uncertainty in the parameter value. It should be noted that the rather large uncertainties listed for certain of the Ai's are the results of small-signal measurements. When these measurements are converted to attenuation ratios and then to their logarithmic equivalents, their uncertainties take on large values. The largest uncertainties in the Ai's are a consequence of curve fitting a slow recovery component to data of limited time duration. In such a case, a relatively wide range of curve slopes appears to fit the measurement.

Conclusion

The radiation responses of seven fibers have been presented, both graphically as measured time histories, and in terms of the $A_i\lambda$ parameter values required to make an exponential recovery model fit the measurements. The $\lambda$ parameters are normalized to unit sample length and radiation fluence and represent the initial peak optical attenuation at 820 ns in a unit length of fiber exposed to a delta function radiation pulse. The $\lambda$ parameters are the exponential time constants that describe the fiber's recovery from the instantaneous darkening producing the optical attenuation.

If a fiber's response to pulsed radiation is linear in length and in dose up to the levels obtained in this experiment, then the sets of normalized response parameters listed in the table for the given fiber and temperature should agree, at least to within measurement uncertainties. The comparisons of parameter sets drawn from the 4 m and 20 m exposures of T303 and T223 fibers for similar bremsstrahlung pulses show agreement to the extent in that corresponding uncertainty intervals overlap. From this, one may conclude that the length and time convolutions described earlier offer a useful means of accounting for the effects of fiber length and radiation time history on transmitted signals. In general, the same cannot be said for the influence of radiation fluence. In the case of the T03 and T223 fibers, the parameter sets drawn from the low-fluence bremsstrahlung and the high-fluence electron beam experiments at room temperature agree within the uncertainties. But for the Corning IVPO and OWPO fibers, recovery time constants observed in the electron-beam experiments are clearly longer than those observed during the bremsstrahlung experiments. The consensus in the literature cited earlier is that induced darkening is dependent on dose, irrespective of the radiation component delivering the dose. If this is the case, then the longer recovery constants for the electron beam experiments are attributable to the very large doses delivered with the electron beam, not the fact that electrons were used to darken the fibers. In retrospect, it is clear that the electron-beam doses were too large to obtain accurate early-time attenuation measurements for several of the more radiation-sensitive fibers. The most accurate measurements and curve fits were obtained when the peak attenuation factors fell in the range of 0.3 to 0.7.

The effects of temperature on the radiation responses of the fibers also followed a complex pattern. For the most part, colder temperatures produced an increase in the peak attenuation, suggesting that recovery mechanisms may be present with characteristic times much shorter than the radiation pulse length, at least at room temperature. Recovery rates for most of the fibers were slower at the colder temperatures, as expected. An apparent exception is the double-window fiber, which showed an anomalous feature at the colder temperature. While the fast-component attenuation parameter, $A_1\lambda$, for this fiber is significantly larger at cold temperature than at room temperature, its recovery rate $\lambda_1$ appears to be a factor of 2 faster than the room-temperature value (this faster recovery explains why in fig. 38 the cold-temperature transmission curve lies above the room-temperature result). Another exception was the T303 fiber, which showed almost no difference in the recovery rates observed at the three test tempera-
References


### Transient Response of Fibers to Pulse Radiation

<table>
<thead>
<tr>
<th>Optical Fiber</th>
<th>Experimental Parameters</th>
<th>Curve Fit Parameters</th>
<th>Transient Response Parameters</th>
<th>Core Dopes</th>
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<td>T(K) 0.68 x-ray 20.0</td>
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<td>A_0(db/m-R)</td>
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*a estimated uncertainty < 30%
*b estimated uncertainty < factor of 2
*c estimated uncertainty < factor of 5
*d estimated uncertainty > factor of 5