Contributed Papers
Bremstrahlung 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 anneal mechanisms with significantly different characteristic times. At room temperature, peak darkening coefficients ranged from $10^{-3}$ to $10^{-5}$ dB/g-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.1-4 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 T203 (a PCS fiber), and the graded-index T223. Four Corning fibers were also tested: the step-index short-distance fiber (SD), and the graded-index IVPO, OVPO, and double-window fiber (DW). All fibers were exposed at room temperature, 295 K, and in addition, the IVPO, OVPO, 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 30 nm FWHM centered on the laser wavelength (802 nm) were interposed between the output ends of the test fibers and the avalanche photodiodes (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-constantan thermocouple junction in direct contact with the metal surface near the fiber.

During the bremsstrahlung tests, several half-kiloenarg 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 effect 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. 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. 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. 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 APO'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 integrating influences 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 \(1-a_1 e^{k_1 t} \), \(1-a_0 e^{k_0 t} \). 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

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

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

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

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

and

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

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 \(D\); \(T_L\) is the time required for light to traverse the fiber segment; the empirical constants \(a_0, a_1, k_0, k_1\) and \(\lambda_1\) 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 \(H(t)\):

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

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 \(a_i's\) and \(\lambda_i's\) are adjusted until a suitable curve fit is obtained. The final values for the \(a_i's\) depend on the total radiation fluence \(D\); this dependence is removed by transforming the \(a_i's\) into the desired differential parameters according to the expression:

\[
A_i = (P/D) 10 \log (1-a_i),
\]

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

\[
\begin{array}{ccc}
\text{Experimental} & \text{Calculated (Optimum Fit)} & \text{Calculated (4m Parameters)} \\
\text{Results} & \text{\(T=295°K\)} & \text{\(D=0.68\text{mR}\)} \\
-L=20.0\text{m} & \text{\(L=4.0\text{m}\)}
\end{array}
\]

Fig. 9 Early response of T-103 fiber (4 m and 20 m lengths) to bremsstrahlung

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.

Fig. 10 Early response of T-223 fiber (4 m 20 m lengths) to bremsstrahlung

Fig. 11 Response of short-distance fiber to electron beam

Fig. 12 Early response of T-103 fiber to electron beam

Fig. 13 Early responses of T-223 fiber to electron beam

Fig. 14 Late responses of T-223 fiber to electron beam
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](image1)

![Fig. 16 Late responses of IVPO fiber to electron beam](image2)

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](image3)

![Fig. 18 Early responses of double window fiber to electron beam](image4)

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 fiber 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 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.

The greater data after 100 ns, which is plotted as solid dots in fig. 18.

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 Corning double-window fiber, which showed an anomalous feature at the colder temperature. While the fast-component attenuation parameter, \( \lambda_0 \), for this fiber is significantly larger at cold temperature than at room temperature, its recovery rate \( \lambda_0 \) appears to be a factor of 10 faster than the room-temperature value (this faster recovery explains why in fig. 18 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-
The variety of behaviors observed when nominally similar fibers were cooled makes an explanation of results in terms of simple physical models quite difficult, if not impossible. Certainly, an extension of this work to measure fiber responses across a continuous range of temperatures and radiation fluences would be very useful in modeling physical processes, as would be the identification of the roles the various dopants and impurities play in determining the net response of the fiber to pulsed radiation.

References

1. "Short-Term Transient Radiation Effects in Optical Fibers," P. B. Lyons et al, presented at Optical Fiber Communication Conference, Washington, D.C., 6 March 1979.

2. "Radiation Response of Large Core Polymer Clad Silica Optical Fibers," G. Sigel et al, IEEE Transactions on Nuclear Science, NS-26, No. 6, pp. 4796-4801, December 1979.

## Table: Transient Response of Fibers to Pulse Radiation

| Optical Fiber | Experimental Parameters | Curve Fit Parameters | Transient Response Parameters | Core Dopants |
|---------------|-------------------------|----------------------|-------------------------------|--------------|
|               | T(K) D(kR) Source L(m)  | t_f Δt               | A_0(dB/m-R) λ_0(s^-1) | A_1(dB/m-R) λ_1(s^-1) | Ge,P |
| ITT T03       |                         |                      |                               |              |
| (Step Index)  | 295 0.68 x-ray 20.0     | 500 ns 1 ns          | 8.9 (-4)^a 1.5 (+7)^a 1.5 (+4)^a 5.0 (+4)^d | Ge,P |
|               | 295 0.62 x-ray 4.0      | 500 ns 1 ns          | 6.6 (-4)^a 1.6 (+7)^a 3.6 (+4)^d 5.0 (+4)^d |
|               | 295 38 electron 0.2     | 500 ns 0.2 ns        | 2.1 (-3)^b 1.9 (+7)^a 4.4 (-4)^a 4.0 (+5)^d |
| ITT T223      |                         |                      |                               |              |
| (Graded Index)| 295 0.55 x-ray 20.0     | 500 ns 1 ns          | 2.0 (-3)^a 2.4 (+7)^a 4.4 (-4)^b 7.5 (+5)^g | Ge,P |
|               | 295 0.45 x-ray 4.0      | 500 ns 1 ns          | 2.7 (-3)^a 5.4 (+7)^a 7.6 (-4)^a 7.5 (+5)^b |
|               | 295 43 electron 0.2     | 500 ns 0.2 ns        | 9.9 (-3)^c 7.0 (+7)^a 9.0 (+4)^b 2.0 (+6)^b |
|               | 295 54 electron 0.2     | 5 μs 0.2 ns          | 4.6 (-3)^c 9.0 (+7)^a 9.6 (-4)^g 1.2 (+6)^b |
|               | 225 55 electron 0.2     | 5 μs 0.2 ns          | 2.3 (-2)^b 5.0 (+6)^b 6.4 (-4)^a 1.4 (+5)^a |
| ITT T03       |                         |                      |                               |              |
| (Step Index)  | 295 44 electron 0.2     | 500 ns 1 ns          | 2.7 (-4)^a 4.2 (+7)^a 6.6 (-5)^b 5.0 (+4)^d | Ge,P |
|               | 295 40 electron 0.2     | 500 ns 1 ns          | 2.0 (-4)^a 4.2 (+7)^a 4.8 (-5)^a 5.0 (+4)^d |
|               | 237 42 electron 0.2     | 500 ns 1 ns          | 3.3 (-4)^a 4.2 (+7)^a 2.0 (+4)^a 5.0 (+4)^d |
|               | 226 57 electron 0.6     | 500 ns 1 ns          | 2.6 (-4)^a 3.6 (+7)^a 7.6 (-5)^b 5.0 (+4)^d |
| COR IVPO      |                         |                      |                               |              |
| (Graded Index)| 295 0.45 x-ray 10.0     | 500 ns 1 ns          | 9.1 (-4)^a 1.1 (+7)^a 2.0 (+4)^a 5.0 (+4)^d | Ge,B,P |
|               | 295 44 electron 0.2     | 500 ns 1 ns          | 1.5 (-3)^a 7.0 (+7)^a 1.0 (+3)^a 3.0 (+6)^b |
|               | 295 40 electron 0.2     | 5 μs 0.2 ns          | 1.4 (-3)^a 7.0 (+7)^a 1.0 (+3)^a 3.0 (+6)^b |
|               | 216 50 electron 0.2     | 5 μs 0.2 ns          | 4.9 (-3)^b 1.0 (+7)^a 9.1 (+4)^a 1.6 (+5)^a |
| COR OVPO      |                         |                      |                               |              |
| (Graded Index)| 295 0.45 x-ray 2.0      | 500 ns 1 ns          | 2.2 (-3)^b 2.9 (+6)^a 1.3 (-2)^a 2.2 (+4)^a | Ge,P |
|               | 295 46 electron 0.2     | 500 ns 1 ns          | 1.3 (-3)^b 2.5 (+1)^b 3.6 (-5)^b 2.0 (0)^b |
|               | 295 48 electron 0.2     | 5 μs 1 ns            | 1.3 (-3)^b 2.5 (+1)^b 3.8 (-5)^b 2.5 (0)^b |
|               | 234 54 electron 0.2     | 5 μs 0.1 s           | 1.8 (-3)^b 9.9 (-2)^b - -
| COR SDF       |                         |                      |                               |              |
| (Graded Index)| 295 43 electron 0.2     | 500 ns 0.2 ns        | 2.0 (-3)^a 1.0 (+2)^a 1.7 (-4)^a 1.2 (+0)^a | Ge,P |
|               |                         |                      |                               |              |
| COR DNP      |                         |                      |                               |              |
| (Graded Index)| 295 42 electron 0.2     | 500 ns 0.2 ns        | 1.1 (-4)^a 5.0 (+7)^a 3.7 (-4)^a 5.0 (+5)^b | Ge,P |
|               | 247 40 electron 0.2     | 500 ns 0.2 ns        | 2.5 (-3)^a 4.5 (+8)^c 3.1 (+4)^a 2.0 (+5)^b |

a estimated uncertainty < 30%
b estimated uncertainty < factor of 2
c estimated uncertainty < factor of 5
d estimated uncertainty > factor of 5