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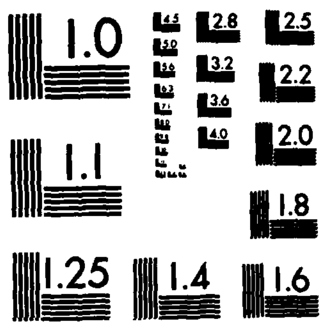

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RADC-TR-84-71
In-House Report
April 1984

ANALYTIC MODELS FOR RADIATION INDUCED LOSS IN OPTICAL FIBERS I

James A. Wall

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

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Analytic models to describe the radiation induced loss in optical fibers as a function of dose were sought. A simple power-law function was tried, and it was found to give excellent to good fits to data on 25 fibers having a wide range of radiation sensitivities. Using this function, only 2 empirical constants are needed to calculate the radiation induced loss in an optical fiber. This is useful in categorizing the radiation hardness of optical fibers and in systems design.

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INDUCED LOSS IN OPTICAL FIBERS I

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Illustrations

Analytic Models for Radiation Induced Loss in Optical Fibers I

1. INTRODUCTION

During a program on the development of radiation-hardened optical fibers,[1, 2, 3] a large amount of data was accumulated on the radiation induced loss in optical fibers as a function of dose. Data taken during the initial phases of the program showed a linear increase in induced loss with increasing dose so that the radiation hardness of the fibers could be characterized by the slopes of plots of the data, that is, dB/km-kilorad. However, as the accuracy of the radiation test procedure was improved, significant departures from linearity were observed in the data, particularly at doses below about 5 kilorads. Nonlinear behavior of induced loss in optical fibers as a function of dose had been reported by others (see Friebele,[4] for example). However, their fiber irradiations were performed at much

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1. Wall, J.A., Posen, H., and Jaeger, R. (1980) The role of the multidopants Sb/P in radiation hardening of optical fibers, Proc. Fiber Optics in the Nuclear Environment Symposium, 25-27 March 1980, DNA 5308P-2, Radiation Phys. 2:31.
2. Wall, J.A., Posen, H., and Jaeger, R. (1981) Radiation hardening of optical fibers using multidopants Sb/P/Ce, in Physics of Fiber Optics, Advances in Ceramics, B. Bendow and S.S. Mitra, Eds. American Ceramic Society 2:393.
3. Wall, J.A., Loretz, T.J., and Mattison, J.E. (1981) Optical fiber composition and radiation hardness, Proc. SPIE 296:35.
4. Friebele, E.J. (1979) Optical fiber waveguides in radiation environments, Optical Eng. 18(No. 6):552.

higher dose rates than ours, and the nonlinearities they observed could be attributed to failure to establish dynamic equilibrium between the trapping (light absorbing) centers and the electron-hole pairs generated during irradiation. The failure to establish dynamic equilibrium during the irradiations resulted in simultaneous generation and annealing of light absorbing centers during irradiation. These results could account for nonlinearity of the data. This could be observed as partial annealing of the induced loss over a period of several minutes following the irradiations, a feature which our data did not show.

An analytic expression to describe the radiation induced loss in optical fibers as a function of dose is important in simplifying the categorization of the radiation hardness of fibers as well as providing the design engineer with a means of determining fiber performance without reference to data plots. Since the linear description of radiation response could no longer be considered a reasonable approximation, other functional relationships were sought. It was found that some workers had reported a dependence of the induced loss on the square root of the dose[5, 6, 7]. Although the data reported by these workers appeared only to approximate the square root of dose dependence, it was decided to attempt a power-law fit to our data.

2. PROCEDURE

The data on radiation induced loss vs dose of 25 optical fibers were fit to the expression

$$L = AD^n \tag{1}$$

where L = induced loss in dB/km

D = dose in kilorads

A, n = constants

A least squares fitting procedure was performed using a hand calculator. The procedure is described in most elementary textbooks on statistics and is outlined here for information.

5. Share, S., and Wasilik, J. (1979) Radiation effects in doped-silica optical waveguides, IEEE Trans. on Nucl. Sci. 26:4802.
6. Gur'yanov, A.N., et al (1978) Radiation-optical stability of low-loss glass-fiber waveguides, Sov. J. Quantum Electronics 8:1401.
7. Gur'yanov et al (1979) Radiation-optical stability of low-loss glass-fiber waveguides, Sov. J. Quantum Electronics 9:768.

Eq. (1) was linearized by taking the logarithm of both sides

$$\text{Log } L = \text{Log } A + n \text{ Log } D \tag{2}$$

define $y = \text{Log } L$
$x = \text{Log } D$
$a = \text{Log } A$

The required constants are then given by:

$$n = \frac{\overline{xy} - \overline{x} \bullet \overline{y}}{\overline{x^2} - \overline{x}^2} \tag{3}$$

$$a = \overline{y} - n \bullet \overline{x}\text{ ; } A = \text{antilog } a \tag{4}$$

where $\overline{x}$ = average value of the x's (Log D's)
$\overline{y}$ = average value of the y's (Log L's)
$\overline{xy}$ = average value of the products of corresponding x's and y's
$\overline{x^2}$ = average value of the squares of the x's

Eq. (3) is most frequently presented in terms of summations over the individual data points in textbooks, but the form given here is more practical for use with basic hand calculators.

Although a correlation coefficient can be calculated as a measure of the "goodness of fit" for each data set, a more definitive evaluation of how well the fitted analytic expression agrees with the data is obtained by calculating the root-mean-square (rms) of the deviations of values calculated using the fitted expression from corresponding values of the data. We define the rms of the deviation as

$$(\overline{\Delta^2})^{1/2} \tag{5}$$

where $\overline{\Delta^2} = \sum_{i=1}^{k} \frac{(Lmi-Lci)^2}{k}$

Lmi = induced loss measured at dose i
Lci = induced loss calculated at dose i
k = number of data points

3. RESULTS

The fits of the data on 25 optical fibers to Eq. (1) ranged from excellent to good. To illustrate the meanings of these qualitative fit evaluations, Figure 1 shows examples of two excellent fits, one example for a relatively radiation sensitive fiber and one for a more radiation "hard" fiber. As can be seen from the figure, the curves calculated from the fits are essentially identical with the plots of the actual data points. Examples of the poorer fits, which we can still call good, are shown in Figure 2 for a similar pair of fibers. Although the fit for the more radiation sensitive fiber tends to overestimate the induced loss at higher doses, and the fit for the more radiation hard fiber underestimates the induced loss at the higher doses, both fits are quite acceptable for the lower doses.

For a more quantitative evaluation of the quality of the fits, the rms deviation of induced losses calculated using the fitted Eq. (1) from the measured induced losses were calculated using Eq. (5). The average rms deviation for all the fibers was 0.698 dB/km with a standard deviation of 0.484 dB/km. Considering that the estimated accuracy of the data was about +2 dB/km, this means Eq. (1) can represent the induced loss as a function of dose very well. In fact, for 17 of the 25 fibers considered, the rms deviation of the fits from the data was less than 1 dB/km.

The quality of the fits is surprising considering that a fairly wide range of radiation sensitivities was covered by the optical fibers observed. This range of sensitivities is illustrated by Wall.[1, 2, 3] To summarize, the group consisted of fibers having germanium-silicate cores doped to varying degrees with boron, phosphorous, antimony, and/or cerium in different amounts and combinations giving a range of radiation sensitivities of about an order of magnitude. Of the two constants required to fit the data to Eq. (1), A was the most variable. For all the fibers, the average value of A was 6.99 with a standard deviation of 4.54.

The higher values of A could be identified with fibers having phosphorous added to the cores. The average value of A for these fibers was 10.32 with a standard deviation of 4.11. For the fibers with boron added to the core, the average of A (omitting one unusually radiation sensitive fiber from the group) was 4.23 with a standard deviation of 1.16. In both cases, the variations in A could only be roughly correlated with the addition of antimony or cerium to the fiber cores. The values obtained for n showed much less spread than those for A. For all 25 fibers, the average value of n was 0.860 with a standard deviation of 0.073. For the phosphorous doped fibers, the average value of n was 0.923 with a standard deviation of 0.045. For the boron doped fibers, the average value was 0.826 with a standard deviation of 0.074. There appeared to be a somewhat better correlation between the values of n and the addition of antimony or cerium to the fiber cores.

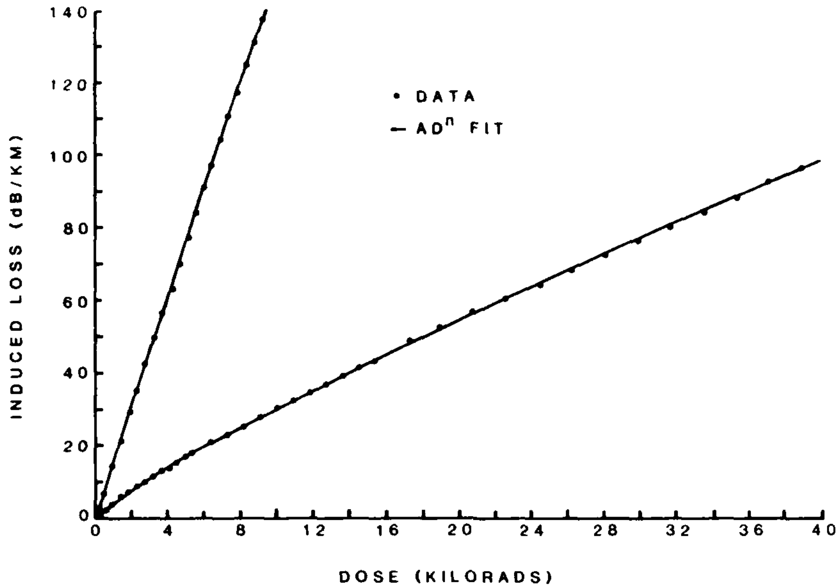

Figure 1. Example of "excellent" fits of Eq. (1) to fiber optic radiation induced loss data

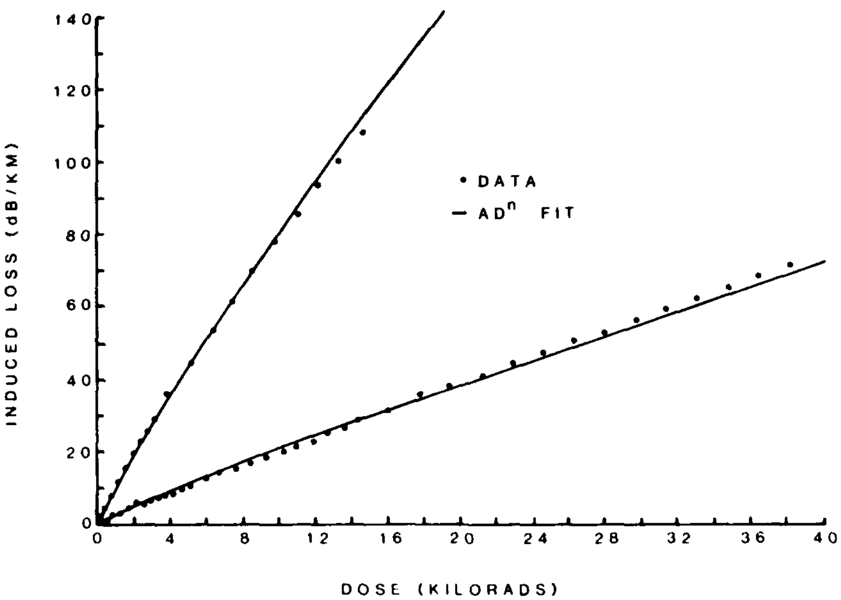

Figure 2. Example of "good" fits of Eq. (1) to fiber optic radiation induced loss data

Both these dopants tended to lower the radiation sensitivities of some fibers, and this generally corresponded with lower values of n.

The foregoing applies to fibers irradiated at room temperature. A limited amount of data was also obtained on some of these fibers irradiated at temperatures of -55° C and +125° C. Eq. (1) could also be fit fairly well to these data. Because of the small amount of data, not much can be said about these results except that the same analytic expression (with different values for the constants) apparently can be applied over these temperature extremes.

4. DISCUSSION

It is surprising that such a simple expression as Eq. (1) can be used to describe the radiation induced loss as a function of dose in a variety of optical fibers of different radiation sensitivities and compositions. At present, we cannot think of any physical reason why this is so.

Those who have, justifiably or not, invoked the square root of dose dependence of induced loss that prompted this study have given two reasons why a simple power law should be applicable to optical fibers. The first rationale[6, 7] is based on a relatively simple model used to explain the creation of F centers (color centers) in crystalline lithium fluoride by X rays.[8] It seems unlikely that this work could be simply extended to the amorphous compound glass from which optical fibers are made. Of course, the model does not apply to optical fibers since it predicts a strict square root of dose dependence, which is apparently not the usual case found for the fibers.

The second rationale[5] is based on the assumption that annealing of the induced loss occurs during irradiation. One calculation has been made[9] based on this assumption for a plastic optical fiber. Transient data on the recovery of induced loss following an X-ray pulse was found to be proportional to t^{-m} where t is the time and m a constant. This was combined with an assumed induced loss generation function to obtain a power law dependence on time and dose-rate that agreed reasonably well with the induced loss data. However, this agreement was probably fortuitous. From our own measurements on transient radiation effects in opti-

8. Durand, P., Farge, Y., and Lambert, M. (1969) The creation of F centers in lithium flouride between 77° and 600° K and their interpretation by a recombination model of interstitial-vacancies, J. Phys. Chem. Solids 30:1353.
9. Kalma, A.H., and Hardwick, W.H. (1976) Radiation testing of a fiber optics data link, IEEE Trans. on Nucl. Sci. 23:1769.

cal fibers[10] and the measurements of others,[7] it is evident that, in general, the recovery of induced loss is not a simple function of time. This is probably because of the presence of different trapping centers with different trap release times in a given fiber. Also, since our fibers, irradiated at much lower dose-rates, showed no recovery following irradiation, the "recovery during irradiation" explanation is not considered applicable.

In spite of the lack of physical justification for the power law dependence of radiation induced loss on dose in optical fibers, the possibility of describing the induced loss data in terms of only two constants is a worthwhile finding for compiling data on the radiation hardness of optical fibers and in opto-electronics system design. However, as with any such simple analytic model, caution must be used in its application because the values for the required constants obtained can be expected to be dependent on irradiation conditions such as dose-rate and, as we already know, temperature.

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10. Wall, J.A., Posen, H., and Jaeger, R. (1981) Temperature Response of germanium phosphosilicate optical fibers under irradiation, in Physics of Fiber Optics, Advances in Ceramics, B. Bendow and S.S. Mitra, Eds., American Ceramic Society 2:398.

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