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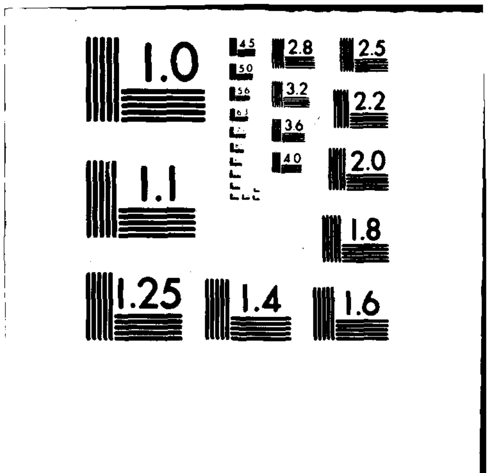

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NUCLEAR RADIATION EFFECTS IN FIBER-OPTIC WAVEGUIDES (U)

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I. Introduction

Fiber-optic communication systems, now under development by the U.S. Army, will be a prime factor in satisfying the Army's communication needs of the 1980's. An important issue for any communication system is survivability: in particular, survivability on the tactical nuclear battlefield. One of the important advantages gained by using fiber optics is their immunity to electromagnetic pulse effects, which are frequently damaging to conventional communication systems operating in tactical nuclear environments. However, glasses in general, and optical fibers in particular, are susceptible to the darkening effects of ionizing radiation found in tactical nuclear weapon environments. This problem is especially serious for Army applications because of the long lengths of cables used in communication systems. Long-haul fiber-optic communication systems are planned by the Army with unrepeatered lengths up to 8 km and data rates of 20 Mb/s(1). Previous fiber radiation data indicate that the use of optical waveguides involving long lengths may be severely affected in nuclear environments. The solution to this problem is an optical waveguide with minimal sensitivity to nuclear radiation.

The purpose of this paper is to identify an optical waveguide which has a good chance for meeting the Army's requirements for a radiation-hardened fiber-optic communication system. To accomplish this goal we have carried out an experimental research program on a wide variety of commercially available optical waveguides and research prototypes. Glass-clad, high-silica fibers, suitable for long-length telecommunications applications, were

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studied. The first step consisted of evaluating the ionizing radiation sensitivity of commercially available glass-clad fibers as a function of fabrication procedure and dopants. Then, after the least radiation-sensitive fiber composition and fabrication procedure was chosen, additional investigations were carried out, primarily on research fibers, to further reduce the ionizing-radiation-induced losses. This was accomplished by selecting a dopant concentration which we judged to have a significant probability of decreasing the fiber's radiation sensitivity.

Our investigation has shown that the radiation losses induced in optical fibers can be greatly reduced by a judicious choice of dopants, by the use of a particular fabrication procedure, and by the wavelength of operation. Recognizing the system requirements and radiation environments, we have chosen a fiber which has a good chance of surviving the nuclear ionizing radiation environment.

II. Fiber-Optic Waveguides

Fiber-optic waveguides are composed of a core material surrounded by a cladding material. The refractive index of the core is always greater than the cladding. Transmission of the optical signal is achieved through light guided in the core because of internal reflections at the core-cladding interface. Current glass-clad fibers are made from silica (SiO_2), whose index of refraction may be raised or lowered by doping with various impurities. Typical index raising dopants include germanium, phosphorus and cesium, and are found in the core. Index lowering dopants include boron and fluorine and are found in the cladding. Several fabrication procedures have been devised to fabricate doped-silica optical fibers with low losses. These include the inside vapor oxidation process or modified chemical vapor deposition (MCVD) process, the outside vapor deposition process, the modified rod-in-tube (MRT) process, the plasma-activated process, and the phase-separable process. The signal bandwidth of a fiber may be controlled by adjusting the index of refraction profile through a gradation of the core and cladding dopants. Before discussing the ionizing radiation response of optical waveguides, we describe the radiation simulation and measurement techniques.

III. Radiation Simulation

The nuclear ionizing radiation was simulated using a ^{60}Co air source (located at the Harry Diamond Laboratories). The losses induced in the fiber were measured during irradiation (i.e., in situ) when the source was brought out of the pool. The annealing of the losses was continuously monitored following the irradiation. Measurements of the losses were carried out over a temperature range from -77 to 100°C; this temperature range includes the military operating range. Measurements were made at wavelengths of 0.8 to 1.3 μm , which includes the range under consideration for operation of fiber-optic communication systems. The radiation dose was obtained using CaF_2 thermoluminescent dosimeters. The radiation effects data obtained on a wide variety of optical waveguides is discussed in the next section.

IV. Fiber Radiation Data

Fabrication Technique and Dopant Dependence

The losses induced at 0.8 μm in a low-loss, commerically available, Corning Glass Works (CGW) fiber from in-situ ^{60}Co radiation are shown in figure 1, as a function of ionizing dose and temperature. The fiber was fabricated by the standard outside process; the core was doped with germanium and boron, and the cladding with boron. As can be seen, the losses induced increase dramatically as the temperature is lowered: the induced losses are more than a factor of 20 smaller at room temperature then at low temperatures (-50°C). The temperature dependence of these curves can be described by a thermally activated diffusion process with an activation energy of 0.55 eV (2). Previous experimenters concerned themselves with measuring the room-temperature radiation response (3,4). Figure 1 shows that at -50°C the losses for a dose of 200 rad(SiO_2) are in excess of 400 dB/km; at room temperature, the induced loss is less than 20 dB/km. These data point out the importance of measuring fiber radiation response over the entire military temperature range. The annealing of the induced losses in this fiber is shown in figure 2. The radiation dose was 2000 rad(SiO_2). Again, the losses increase as the temperature is decreased. At 1000 s after ^{60}Co irradiation, the losses are in excess of 200 dB/km at -50°C; at 22°C the losses decrease to less than 10 dB/km. These data illustrate that if optical communication systems are to be operational at low temperatures typically found in military applications, as well as in radiation environments, a means must be found to reduce the large losses that occur below room temperature.

Figure 3 shows the losses induced from in-situ ^{60}Co irradiation as a function of ionizing dose in a CGW fiber doped with germanium, boron, and phosphorus in the core and fabricated by the standard inside process. Here it is seen that the temperature

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dependence of the losses at low temperatures (<-30°C) is reduced compared to the previous fiber (in Fig. 1): this is attributed to the addition of the phosphorus. The losses at 2000 rad(SiO_2) are approximately 300 dB/km at -50°C and are about six times smaller than in the previous Ge-B-doped fiber fabricated by the outside process. The annealing of the induced losses is shown in figure 4. A similar temperature independence is observed here as in the in-situ radiation experiments.

These results demonstrate that the radiation response of fiber-optic waveguides over the miliary temperature range depends on dopant composition and waveguide fabrication techniques. For this reason similar radiation measurements were performed on other commercially available optical waveguides, having a wide range of dopants and standard industry fabrication procedures (5). The fibers are listed in Table I, along with vendor, core dopant, cladding dopant, and fabrication procedure; the intrinsic loss and bandwidth are listed in Table II. The CGW fibers have been discussed. The International Telephone and Telegraph (ITT) fiber contained phosphorus and germanium in the core and was fabricated by the inside process. The Times Wire and Cable (TWC) fiber, Valtec (VAL) fiber* and the Dainichi-Nippon Cables (DNC) fiber have silica cores with boron and/or fluorine in the cladding. They are fabricated by the outside, plasma-activated, and modified rod-in-tube (MRT) process respectively. Also listed is a Canstar (CAN) fiber fabricated by the phase-separable technique. Several research fibers (BTL and HRL) are listed and will be discussed later.

Figures 5 and 6 show the losses induced at 0.8 μm in the commercially available fibers from 200-rad(SiO_2) in-situ ^{60}Co irradiation and at 1000 s following a 2000-rad(SiO_2) ^{60}Co irradiation as a function of temperature. The CGW and TWC fibers, both fabricated by the outside process, show large losses at low temperatures for both measurement conditions. The losses induced in the fibers containing F (i.e., Valtec and Dainichi-Nippon) showed large losses at low temperatures in the 1000 s recovery experiment. The phase-separable Canstar fiber has losses nearly similar to the P-doped ITT fiber at 1000 s following the ^{60}Co radiation, but the in-situ ^{60}Co induced losses are considerably lower in the ITT fiber than in the Canstar fiber.

**The F-doped Valtec fiber was manufactured from a Hereaus-Amersil, Inc. preform.*

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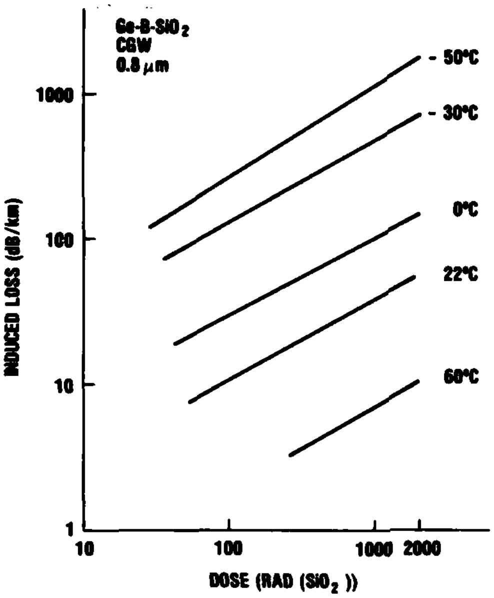

Figure 1. Induced loss at 0.8 μm in CGW Ge-B-SiO_2 fiber from in-situ ^{60}Co irradiation at various temperatures. The ^{60}Co dose rate was 95 rad(SiO_2)/s.

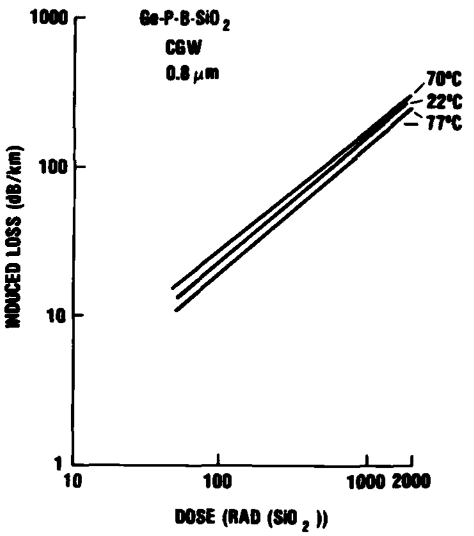

Figure 3. Induced loss at 0.8 μm in CGW Ge-P-B-SiO_2 fiber from in-situ ^{60}Co irradiation at various temperatures. The ^{60}Co dose rate was 95 rad(SiO_2)/s.

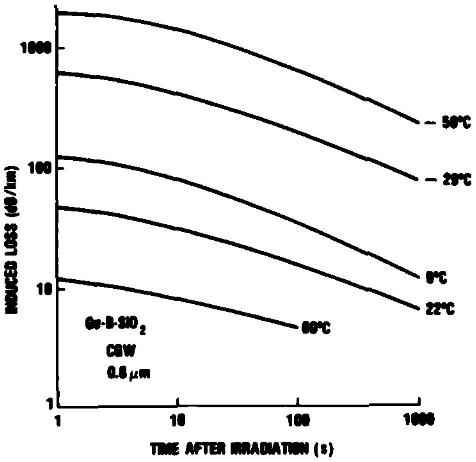

Figure 2. Induced loss at 0.8 μm in CGW Ge-B-SiO_2 fiber versus time after 2000 rad(SiO_2) ^{60}Co irradiation at various temperatures.

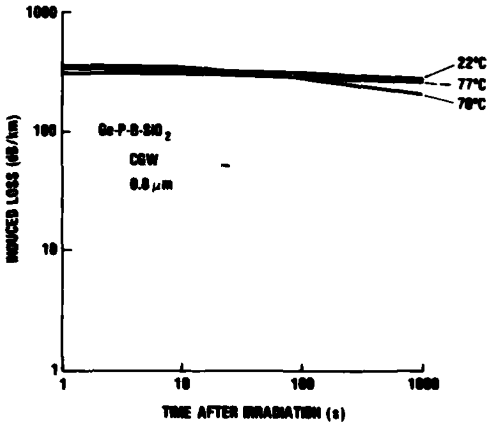

Figure 4. Induced loss at 0.8 μm in CGW Ge-P-B-SiO_2 fiber versus time after 2000 rad(SiO_2) ^{60}Co irradiation at various temperatures.

Table I. Fiber Composition and Fabrication Procedure

Vendor	Composition		Fabrication Procedure
	Core	Cladding	
CGW	Ge-B-SiO_2	B-SiO_2	Outside
CGW	Ge-P-B-SiO_2	B-SiO_2	Inside
ITT	Ge-P-SiO_2	B-SiO_2	Inside
DNC	SiO_2	B-F-SiO_2	MRT
TWC	SiO_2	B-SiO_2	Outside
VAL	SiO_2	F-SiO_2	Plasma-Act.
CAN	Cs-SiO_2	doped-SiO_2	Phase-Sep.
BTL	Ge-P-SiO_2	B-SiO_2	Inside
HRL	Ge-P-SiO_2	B-SiO_2	Inside

Table II. Optical Characteristics of Fibers

Vendor	Intrinsic loss at 0.82 μm (dB/km)	Bandwidth (3dB) for 1 km length (MHz)
CGW	5	270
CGW	4	220
ITT	~5	150
DNC	~3	800**
TWC	~4	200
VAL	~3.5	45
CAN	~17*	15
BTL	~6	--
HRL	~10	--

*at 0.89 μm
**6 dB

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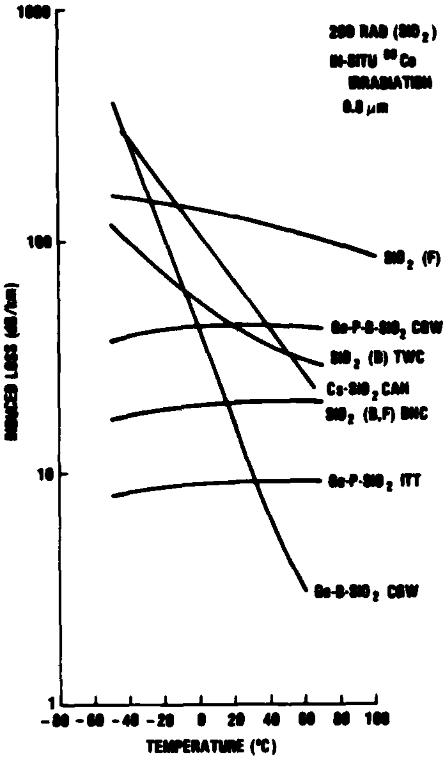

Figure 5. Induced loss at 0.8 μm in several fibers from 200 rad(SiO_2) in-situ ^{60}Co irradiation at various temperatures. The elements in parentheses are cladding dopants.

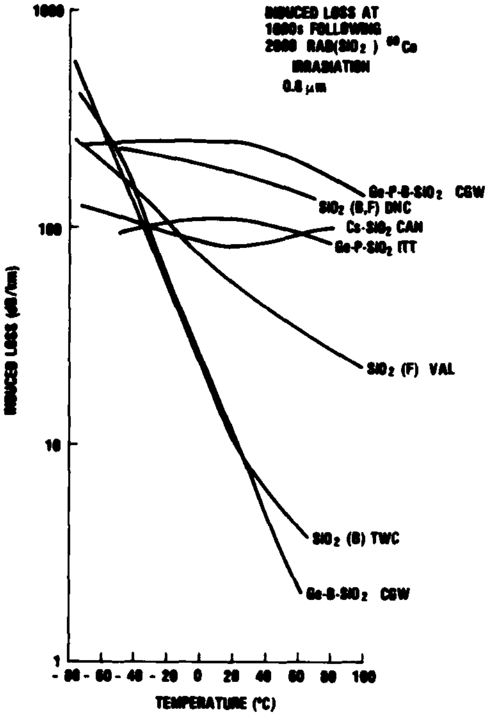

Figure 6. Induced loss at 0.8 μm in several fibers at 1000 s following 2000 rad(SiO_2) irradiation at various temperatures. The elements in parentheses are cladding dopants.

These results suggest that a Ge-doped fiber containing phosphorus and fabricated by the MCVD process (inside process) could yield a fiber with a low radiation sensitivity. To further explore this, several Ge-doped fibers with different phosphorus content were examined. Figures 7 and 8 compare the losses induced at 0.8 μm in several P-doped fibers from 200-rad(SiO_2) in-situ ^{60}Co irradiation and at 1000 s following a 2000-rad(SiO_2) irradiation. The Bell Telephone Laboratories (BTL) and Hughes Research Laboratories (HRL) fibers are research fibers; the ITT fiber was shown previously (in Fig. 5 and 6). These fibers were all fabricated by

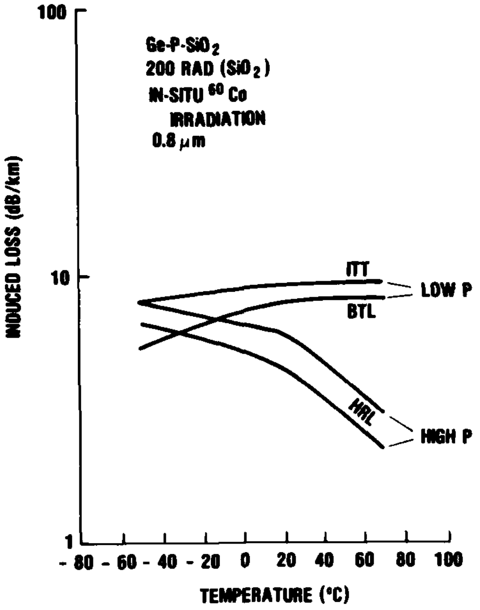

Figure 7. Induced loss at 0.8 μm in Ge-P-SiO_2 fibers from 200 rad(SiO_2) in situ ^{60}Co irradiation at various temperatures.

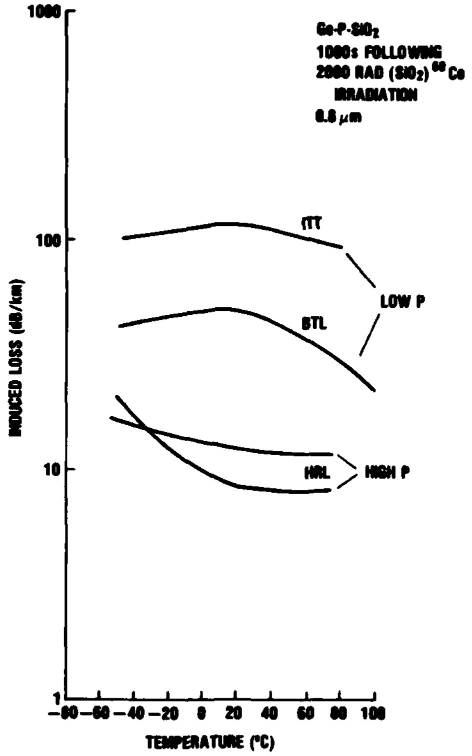

Figure 8. Induced loss at 0.8 μm in Ge-P-SiO_2 fibers following 2000 rad(SiO_2) ^{60}Co irradiation at various temperatures.

the MCVD technique, and had different phosphorus content in the core. The ITT and BTL fibers had low phosphorus concentration; the HRL fibers had high phosphorus concentration. All the fibers had similar germanium content in the core except the BTL fiber which had somewhat more. The cladding of these fibers was all doped with boron. The intrinsic losses (at 0.8 μm) of the BTL and HRL fibers were 6 and 10 dB/km; the ITT fiber was 5 dB/km. The bandwidth of the HRL fibers was probably less than that of BTL and ITT fibers because the HRL fibers have a layered index profile (e.g. step or W)(6) while the ITT and BTL fibers have graded index profiles. From figure 8, we can see that the HRL fibers show much lower induced losses at 1000 s following ^{60}Co irradiation than the ITT and BTL fibers: the losses induced in the HRL fibers were more than a factor of five less than those observed in the ITT fiber over the temperature range of the measurements. The losses measured during 200-rad(SiO_2) ^{60}Co irradiation (in Fig. 7) show the reduced sensitivity of HRL fibers compared with the ITT fiber. This becomes more apparent as the temperature is increased.

These data show that a Ge-doped fiber with a high phosphorus content has an improved radiation response, especially in recovery from the induced losses following irradiation, compared with low-phosphorus-content fibers. However, these fibers also have different index profiles. Whether this plays a role in the radiation response of these fibers is under investigation. At any rate Ge-doped fibers manufactured by the MCVD process and with a high phosphorus content show the lowest radiation sensitivity of the fibers evaluated.

Wavelength Dependence

In general, the radiation response of glass and optical waveguides depends on wavelength. The spectral dependence of the radiation losses induced in the low P BTL fiber and the high P HRL fiber is shown in figure 9. The losses are given relative to 0.8 μm in the wavelength range from 0.8 to 1.06 μm. The radiation dose was 2000 rad(SiO_2); the radiation temperature was 22°C. As seen, the induced losses tend to decrease as the wavelength increases from 0.8 to 1.06 μm. Similar results were observed at other temperatures. Data taken at longer wavelengths (1.3 μm) on the high-phosphorus content Ge-doped fiber revealed that losses increased beyond 1.06 μm and were similar to those observed at 0.9 μm. Considering only the fiber, these results indicate that the most desirable wavelength for operation in a radiation environment is at 1.06 μm. However, consideration must be given to other system characteristics (sec. V).

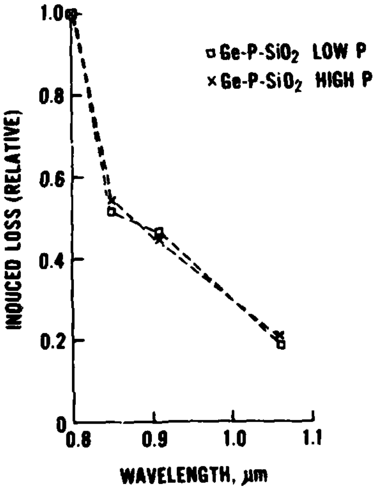

Figure 9. Spectral dependence of induced loss for Ge-P-SiO_2 fibers. The radiation dose was 2000 rad(SiO_2); the radiation temperature was 22°C.

V. Discussion

The fiber-optic response data shows that a high-phosphorus-content Ge-doped waveguide fabricated by the MCVD technique gives the lowest radiation response of the fibers measured. Selection of the optimum operating wavelength depends not only on the fiber radiation response but also on other system parameters. These include emitter output, receiver sensitivity, component degradation, and the intrinsic preirradiation losses of the fiber. From the spectral dependence of the radiation response data in figure 9, it appears that operation at long wavelengths, especially at 1.06 μm, would be beneficial. However, the emitter and detector performance must be considered. It is desirable to use an emitter with as high an output power as possible. Currently GaAlAs lasers operating from 0.8 to 0.89 μm yield the highest output power. For wavelengths beyond 0.9 μm to 1.06 μm, light-emitting diodes (LED's) are used primarily because lasers operating in this regime at present have short lifetimes. Approximately 15 dB more power can be coupled into a fiber with a 0.8 to 0.89 μm laser emitter than with an LED emitter at 1.06 μm. The sensitivity of silicon photodiode detectors used in optical receivers also decreases at longer wavelengths. Even though the 1.06-μm fiber radiation losses are less than those occurring at shorter wavelengths, the reduction is not enough to offset the superior performance of the 0.8 to 0.89 μm emitter and receiver components. Therefore, within current emitter and detector technology, and taking into account that the fiber radiation response decreases as the wavelength increases, operation near 0.9 μm with an injection laser would be preferred in a radiation environment.

It was noted that the losses induced in the high-phosphorus fiber increase for wavelengths greater than 1.06 μm: the 1.3 μm radiation losses were similar to the 0.9 μm losses. However, because of the low sensitivity of the receivers currently used at 1.3 μm and the smaller emitter output compared with those used in the 0.8 to 0.89 μm region, operation near 0.9 μm appears to be advantageous where radiation survivability is desired. If research now being conducted to improve device performance at 1.3 μm should yield suitable detectors and emitters, then operation at 1.3 μm may become more desirable, especially since intrinsic fiber losses are minimal at this wavelength.

To assess fiber survivabilility, it is useful to determine the total loss which might be induced in a given length of fiber when exposed to a particular radiation environment. As an example two cases will be considered: (1) the losses induced in a length of fiber following nonuniform irradiation from a point source and (2) the losses induced during irradiation in a fiber uniformly exposed over its length. The first case could apply to an initial nuclear weapon environment, the second to a residual radiation (fallout) environment. The length of fiber we considered is that typically found in long haul communication applications, 4 km. If we choose a high-phosphorus-content Ge-doped fiber operating in the 0.85 to 0.9 μm wavelength region, the losses remaining at 1000 s following a nonuniform irradiation from a point source are 12 to 15 dB throughout the military temperature range. We choose the peak radiation dose in the center of the fiber to be 2000 rad(SiO_2). The magnitude of the losses are determined by the low-temperature (-50°C) fiber response. Extending the length of fiber does not significantly increase the losses because the radiation field of a point source decreases rapidly with distance. In the second case if we choose a uniform exposure of 200 rad(SiO_2) over the high-phosphorus-content fiber operating in the 0.85 to 0.9 μm range, the induced losses range from 9 to 12 dB for a 4 km length. Increasing the length of fiber in this case increases the losses.

The overall losses that can be sustained by the system from irradiation are determined by many system parameters: pre-irradiation cabled fiber loss, receiver sensitivity, connector losses, component degradation, bandwidth, and emitter output power, to name a few. Also, consideration must be given to the radiation degradation of other components, such as receivers, in determining the loss margin that should be allotted to radiation losses in the fiber. Using system parameters for present commercially available fiber-optic technology, the margin that could be allowed for radiation effects in a 4 km system operating at 20 Mb/s is 16 to 18 dB over the 0.85 to 0.9 μm wavelength range. The losses induced in the high-phosphorus research prototype fiber by the two radiation environments discussed above have similar values. This result points to the possibility that a fiber may be found that could be used in a long haul radiation environment. We would like to point out that more work is needed, but compared to the situation that existed two years ago (at the outset of this study) where fiber radiation losses (see fig. 1 to 4) were around several hundred dB/km, things are greatly improved; said in another way, the nuclear-radiation-survivable length of fiber has increased by more than a factor of 20. Additional work is needed to improve the intrinsic loss and bandwidth of the high-phosphorus Ge-doped fiber so that it can meet system performance parameters. Also the radiation effects in the receiver must be considered in the total system response.

VI. Summary

An investigation was made of the response of optical waveguides to ionizing radiation for different fiber compositions, fiber fabrication techniques, and wavelengths. Our research has shown that large radiation-induced losses occurring in commercially available fibers could be greatly reduced using research fibers fabricated by the MCVD process and doped with germanium and and a large concentration of phosphorus. Analysis shows that a 4 km length of this type of fiber exposed to a nuclear radiation environment produces losses in the fiber at 0.85 to 0.9 μm which are within operating expectations of systems now under development. With additional work to reduce the intrinsic losses and to increase the bandwidth, an MCVD Ge-doped fiber containing phosphorus has a good chance of satisfying the Army's need for a radiation-hardened fiber.

Acknowledgement

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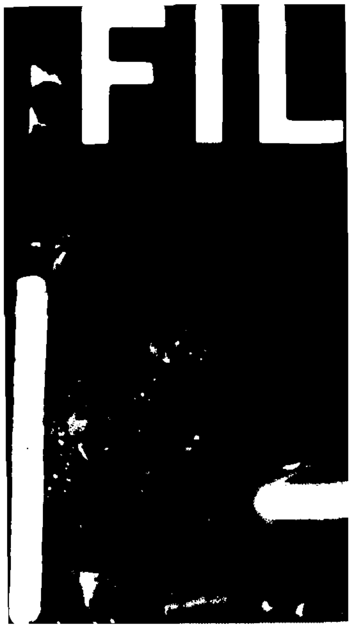
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