PERFORMANCE OF OPTICAL FIBERS IN SPACE RADIATION ENVIRONMENT

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ABSTRACT

The use of optical fibers in low earth orbiting (LEO) satellites is a source of concern due to the radiation environment in which these satellites operate and the reliability of devices based on these fibers. Although radiation induced damage in optical fibers cannot be avoided, it can certainly be minimized by intelligent engineering. Qualifying fibers for use in space is both time consuming and expensive, and manufacturers of satellites and their payloads have started to ask for radiation performance data from optical fiber vendors. Over time, Nufern has developed fiber designs, compositions and processes to make radiation hard fibers. Radiation performance data of a variety of fibers that find application in space radiation environment are presented.

1. INTRODUCTION

There appears to be a significant amount of interest in the use of low earth orbiting (LEO) satellites to carry out missions in areas as diverse as earth sciences and technology, remote imaging and sensing, national security, commercial communications, etc [1]. All the aforementioned applications rely heavily on the use of onboard photonic devices and systems. As a result, onboard use of optical fibers in the form of fiber lasers, fiber amplifiers, fiber sensors, etc. is increasing significantly. Similarly, utility of optical fiber in onboard data processing, communication and transmission equipments is also increasing dramatically. The extensive use of optical fibers in LEO satellites is a source of concern because of the environment in which these satellites operate and the uncertainty about component, device and system reliability in such environments [2]. These satellites may operate at altitudes of 100-50000 miles (depending on the mission) and therefore, may pass through the radiation belt which primarily contains energetic protons [3]. Optical fibers go dark upon exposure to ionizing radiation, as a result of the production of color centers. Although optical fiber performance will depend strictly on the actual mission radiation environment, it is safe to assume that the average radiation dose rate received by the shielded interior of a typical satellite is ~0.05 Rad/min [4]. For a 5-10 year mission lifetime, this translates to a total accumulated dose of 125-250 kRad, which is sufficient to degrade the performance of the spacecraft's optical components.

Since radiation induced damage depends on glass composition and processing, it varies from fiber to fiber and also from vendor to vendor for the same fiber. Significant amount of work has been carried out to characterize the performance of optical fibers in various radiation environments. Qualifying the fibers for use in space is time consuming and expensive. The situation is further aggravated by the fact that some vendors of such optical fibers have ceased to exist or have shifted priorities, resulting in a scarcity of such fibers and radiation data. Many of the fibers qualified in the past are no longer available.

Except for critical missions, constraints of time and money practically mandate the use of COTS (commercial-off-the-shelf) components as the only viable option. Manufacturers of satellites and their payloads have already started to demand radiation performance data on components from the individual component vendors. As an independent manufacturer of both passive and active specialty optical fibers, Nufern is beginning to address this issue. Over the years, Nufern has developed fiber designs, compositions and processes to make radiation hard fibers. Radiation performance data (both gamma and proton) of a variety of single mode (SM), multimode (MM), and polarization maintaining (PM) fibers, that find applications in space environments, are presented.

2. EXPERIMENTAL

2.1 Tested Fibers

The Nufern fibers that were tested for resistance against gamma and proton radiation induced attenuation are listed in Table 1. Details on the

Table 1. Tested fibers.

Fiber	Radiation
S1550-HTA (SM)	γ & Proton
R1310-HTA (SM)	γ
GR50/125-23-HTA (MM)	γ
GR62.5/125-27-HTA (MM)	γ
GR100/140-24-HTA (MM)	γ
PM1550G-80 (SM)	γ
PM850G-80 (SM)	γ

specifications of these fibers can be found on Nufern's website [5]. Two reference fibers were also tested (one each in γ- and proton radiation environment). These were Corning's SMF28® and Sumitomo's Z-fiber® [6], respectively.

2.2 Gamma Radiation Testing

The gamma radiation facility used for testing was an irradiation room having a volume of 14.5 m^3. A wide range of dose rates (100 Rad/hr - 1 MRad/hr) from a Co^{60} source were available. Several small ports penetrated one shielding wall to provide access for instrumentation cables. Test fiber was wound on a 150-mm diameter spool which was mounted on a shaft that rotated it back-and-forth on its central axis by 360° at a rate of ~0.6 rpm in order to directly expose the entire length of fiber to gamma radiation. Dosimetry mapping was performed to determine the uniformity of the gamma radiation dose rate over the spool. Bruker Biopsin Alanine pellets were used as dosimeters.

An OTDR (PK Model 6500) was used for loss measurements of all the fibers except PM850G-80. The fiber under measurement was spliced to a lead fiber (SMF28®) spool to extend the length of the signal, thereby improving measurement accuracy. Radiation induced attenuation of PM850G-80 fiber at 830 nm was measured using a Qphotonics SLED source (820 nm), Agilent Model 81624A InGaAs detector and an Agilent Lightwave multimeter Model 8160A with 81619A interface. Input power was below 1 μW (30 dBm) to avoid photobleaching effects.

Average dose rate used was ~2 Rad/sec and data was accumulated to a total dose of 50 kRad. All measurements were carried out at room temperature.

2.3 Proton Radiation Testing

Measurements were also carried out in a proton accelerator facility. The proton beam diameter over which the energy was uniform was 100-mm. Several small ports penetrated one shielding wall to provide access for instrumentation cables. Both fibers (S1550-HTA and Z-fiber®) were wound on a custom Plexiglas spool of a "wedding cake" design. The spool was precisely aligned with a laser that was coaxial with the proton beam. This allowed simultaneous exposure of both the fibers without energy loss due to shadowing.

Transmission of the fibers was monitored simultaneously and continuously during and after the end of exposure. LEDs were centered at 1570 nm. Protons in the beam had energy of 55 MeV, proton flux was ~1.1x10^8/cm^2-s corresponding to gamma dose rate of ~33 Rad/sec, and proton fluence was ~1.47x10^{12}/cm^2 corresponding to ~500 kRad. During and after the irradiation, temperature was held at ~27°C.

3. RESULTS AND DISCUSSION

3.1 Gamma Testing of SM Fibers

S1550-HTA is a SM pure silica core fiber containing fluorine down-doped cladding and is considered as a "radiation hard" fiber. It finds applications in optical fiber sensors where the fiber is likely to be exposed to extremely high dose rates and total doses. R1310-HTA is also a SM fiber that is optically and mechanically similar to SMF28® but is manufactured in a manner to impart higher radiation resistance in comparison to SMF28®. It is considered as a "radiation tolerant" fiber and is designed to replace SMF28® in applications where ionizing radiation is a cause of concern.

Induced attenuation versus accumulated dose plots of S1550-HTA, R1310-HTA and SMF28® fibers at 1550 nm are presented in Fig. 1. Solid lines represent best-fit to the data. In case of S1550-HTA, data is well represented by a three-term "saturating exponentials" model [7]:

$$A = \sum_i a_i [1 - \exp(-D/\tau_i)] \qquad (1)$$

where A is the induced attenuation, D is the

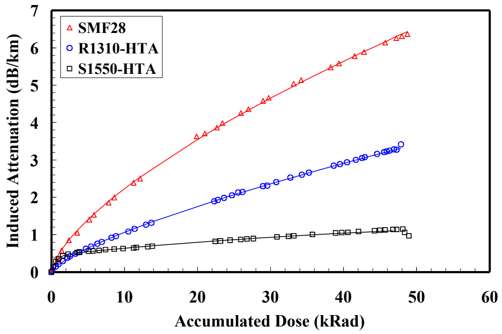

Fig. 1. γ-radiation data of the SM fibers.

accumulated dose, and a_i and τ_i are the best fit parameters describing the amplitude and the saturating dose, respectively of the different exponentials. Each term represents an absorbing defect. In case of R1310-HTA and SMF28®, data is well represented by a much simpler "power law" model [8]:

$$A = \alpha D^{\beta} \tag{2}$$

where α and β are the best fit parameters describing the power function. Best fit constants for all the three fibers are presented in Table 2.

Table 2. Fitting parameters of the SM fibers.

Fiber	Parameters
S1550-HTA	a_1: 0.4444; τ_1: 0.6601
	a_2: 1.1425; τ_2: 52.182
	a_3: 0.0000; τ_3: 1070.19
R1310-HTA	α: 0.1995; β: 0.7264
SMF28®	α: 0.4786; β: 0.6687

First, the radiation data of SMF28 acquired in this study is compared with the data available in published literature. It is difficult to make the comparison because of vast differences in dose rates, total doses, and testing temperatures. However, if data is available at two dose rates, it is possible to extract radiation induced attenuation at any given dose rate and total dose. The dose rate dependent constant α in Eq. 2 is described by the following equation [9]:

$$\alpha = \alpha_o [\phi]^{(1-\beta)/n} \tag{3}$$

where α_o is the dose rate independent constant, ϕ is the dose rate and n is the kinetic order of recovery (usually 1 or 2). If a value of n is assumed and a minimum of two sets of data (ϕ_1, D_1, A_1) and (ϕ_2, D_2, A_2) are available, then it is possible to determine the values of α_o and β for predicting A at any value of ϕ and D. A comparison is shown in Table 3. Actual data is presented in regular style while extrapolated data (under conditions similar to those used by Nufern) using the method described above is shown in italics. Data collected by Nufern is also shown. Data compiled in this study seems to be in line with the number extracted from data reported in the literature [10].

Table 3. SMF28® radiation data comparison.

Source	Rad/min	kRad	T (ºC)	dB/km
Nufern	127.8	50	23	6.55
Ref. 10	0.10	100	25	2.96
Ref. 10	0.01	100	25	2.10
Ref. 10	*127.8*	*50*	*25*	*4.77*

According to Fig. 1, under similar irradiation conditions, S1550-HTA fiber is superior to both R1310-HTA and SMF28®. At a dose rate of ~ 2.13 Rad/sec, attenuation of S1550-HTA fiber increases rapidly to ~0.5 dB/km at a total dose of ~2.25 kRad where it reaches saturation. From there on, attenuation increases slowly till it reaches ~1.1 dB/km at ~50 kRad. At lower dose rate exposures, this fiber will certainly reach saturation at much lower total doses. The only meaningful comparison can be made with Sumitomo's Z-fiber® (SM, pure silica core fiber) that is considered as a high radiation hardness fiber. The gamma radiation induced attenuation of this fiber at room temperature is ~1.5 dB/km when tested at a dose rate of 27.78 Rad/sec and after a total accumulated dose of 100 kRad [6]. At the same accumulated dose, but at an order of magnitude lower dose rate, induced attenuation of S1550-HTA fiber is predicted to be 1.4 dB/km (by using Eq. 1 and the data in Table 2).

With respect to R1310-HTA fiber, data in Fig. 1 and Table 2 clearly indicates the superior radiation hardness of Nufern fiber as opposed to that of SMF28® under similar irradiation conditions. There is at least one fiber manufactured by J-Fiber which is similar to SMF28® and is marketed as radiation resistant SM fiber [11]. Gamma radiation induced attenuation of this fiber at 1550 nm and room temperature is <30 dB/km after exposure at a dose rate of 73 Rads/sec and a total accumulated dose of 1 MRad. At the same accumulated dose but ~34X lower dose rate, induced attenuation of R1310-HTA fiber is predicted to be ~30 dB/km (using Eq. 2 and data in Table 2).

3.2 Gamma Testing of MM Fibers

Nufern manufactures both standard and “radiation tolerant” versions of MM fibers having graded-index profiles. The radiation tolerant versions tested in this study included the 50/125, 62.5/125 and the 100/140 type. All the three MM fibers are designed for short-reach interconnects to be used in the aerospace arena. The bandwidths of these fibers at the two wavelengths of interest are presented in Table 4.

Table 4. Bandwidths of the MM fibers.

Wavelength (nm)	Bandwidth (MHz-km)		
	50/125	62.5/125	100/140
850	≥1000	≥160	≥200
1300	≥300	≥500	≥200

Radiation induced attenuation versus total accumulated dose data for the three fibers at 850 nm and 1300 nm wavelengths are shown in Fig. 2 and Fig. 3, respectively. Up to a total dose of <50 kRad, all three fibers exhibit induced attenuation that increases with accumulated dose. At 850 nm, increase is linear ($A = mD$, where m is the slope of the A versus D plot) where as at 1300 nm, increase follows the power law model (Eq. 2). Best fit parameters of all the three MM fibers at the two wavelengths are presented in Table 5. The MM fibers exhibit much higher radiation induced attenuation, particularly at the lower wavelength. Fortunately, these MM fibers, which need to be radiation hardened, are used as relatively short links. At 850 nm and up to 40 kRad, these fibers are far from reaching saturation. Similarly, at 1300 nm and up to 40 kRad, the fibers show no signs of saturation. In reference 10, gamma radiation hardness data is compiled for different types of MM fibers from various vendors at room temperature and at the two wavelengths. Again, comparison becomes difficult because of the widely different irradiation conditions. However, data is given for two of the OFS fibers at two different dose rates that allow estimation of the induced loss under the conditions used in this study. Actual data is reproduced in Table 6 (in regular style) along with the values estimated using Eq. 3 (in italics). Nufern data is also presented. At 1300 nm, both the Nufern fibers exhibit superior radiation hardness than the competing fibers. At least one of the OFS fibers (BF04431®) does not appear to be of the radiation tolerant design.

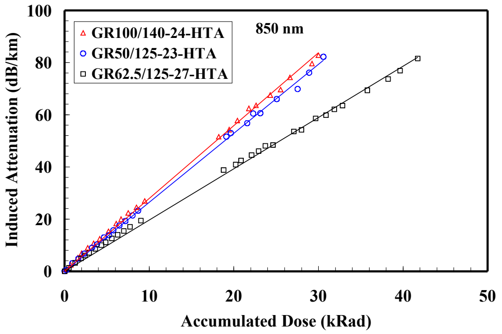

Fig. 2. γ-radiation data of MM fibers at 850 nm.

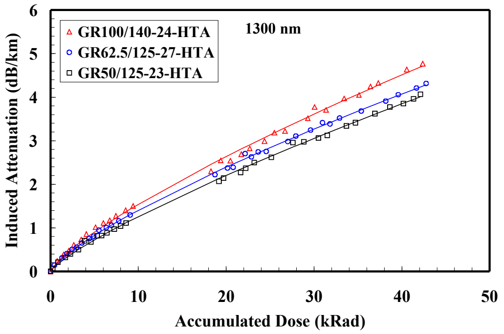

Fig. 3. γ-radiation data of MM fibers at 1300 nm.

Table 5. Fitting parameters of the MM fibers.

Fiber	850 nm	1300 nm
GR50/125-23-HTA	m: 2.645	α: 0.198; β: 0.804
GR62.5/125-27-HT	m: 1.966	α: 0.241; β: 0.767
GR100/140-24-HTA	m: 2.790	α: 0.259; β: 0.774

Table 6. Radiation data of MM fibers at 1300 nm.

Fiber	Designation	Rad/sec	kRad	dB/m
62.5/125	BF04431®*	0.54	46.8	581
62.5/125	BF04431®*	0.083	37.1	498
62.5/125	*BF04431*®*	*2.16*	*50*	*583*
62.6/125	GR62.5/125-25-HTA**	2.16	50	4.84
100/140	BF05444®*	0.83	100	9.6
100/140	BF05444®*	0.567	100	6.45
100/140	*BF05444*®*	*2.16*	*50*	*21*
100/140	GR100/140-24-HTA**	2.16	50	5.35

*OFS; ** Nufern

3.3 Gamma Testing of PM Fibers

The PM fibers designated as PM1550G-80 and PM850G-80 are Panda style, 80 µm diameter, gyro-grade quality fibers that are designed to wind coils for high precision interferometric fiber optic gyroscopes (IFOGs) operating at 1550 nm and 830 nm, respectively. Induced attenuation versus accumulated dose plots of the two fibers are presented in Fig. 4. Once again, data for PM1550G-80 fiber (at 1550 nm) can be represented well by the "power law" model while data for PM850G-80 (at 830 nm) follows the linear model. Best fit parameters of both the PM fibers at the two wavelengths are presented in Table 7. Some information is available in the literature on the performances of PM fibers in γ-radiation environment. Reference 10 provides such data for a number of PM fibers. The data is reproduced in Table 8 along with the data for Nufern fibers. The two 3M fibers are of the elliptical cladding design for operation at 1550 nm (FS-PM-762®) and at 830 nm (FS-PM4611®). These are however, 125 µm diameter fibers for telecom applications. The comparison is made difficult by the widely different irradiation conditions. The Fibercore product (HB800®) is of the bow-type design and is an 80 µm size gyro-fiber. Although one-on-one comparison is difficult because of the widely different irradiation conditions, photobleaching effects were present in the Fibercore fiber [10], perhaps yielding an artificially lower induced attenuation.

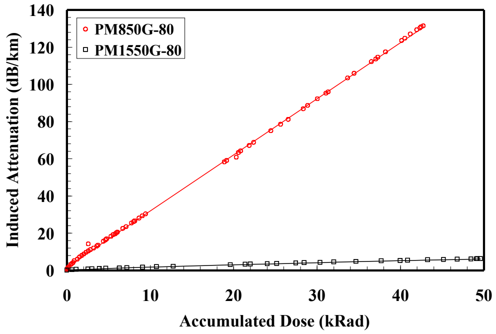

Fig. 4. γ-radiation data of PM1550G-80 (at 1550 nm) and of PM850G-80 (at 830 nm).

Table 7. Fitting parameters for the PM fibers.

Fiber	Parameter
PM1550G-80	α: 0.270; β: 0.800 @ 1550 nm
PM850G-80	m: 3.023 @830 nm

Table 8. Radiation data of PM fibers.

Fiber	Source	Rad/sec	kRad	dB/m
PM1550G-80	Nufern	2.1	50	6.2
FS-PM-7621	3M	175	500	20
FS-PM-7621	3M	175	5000	55
PM850G-80	Nufern	2.1	50	151
FS-PM4611	3M	0.2	17	47
FS-PM4611	3M	0.2	200	170
HB800®	Fibercore	21.2	10	45.6

3.4 Proton Testing of SM Fibers

The near-earth space in which the satellites operate is dominated by energetic protons. However, radiation tolerance measurements are usually performed using γ-radiation because of the ready availability of such facilities. Another reason for the use of γ-radiation is the assumption that it provides a worse case scenario as compared to proton exposure. Past studies with proton irradiation have indeed determined that pure silica core and some doped fibers perform similarly or even better in comparison with exposure to γ-radiation. The proton radiation sensitivity of Nufern S1550-HTA fiber was measured and compared with the similar data obtained in γ-radiation environment. Sumitomo's Z-fiber® was also tested for reference purposes.

Both growth and recovery data were collected. Attenuation versus time (both growth and recovery) plots are shown in Fig. 5. S1550-HTA is somewhat more sensitive to radiation induced attenuation growth relative to Z-fiber® (reaching the same induced loss at earlier times), but it also recovers at a faster pace. This makes this fiber attractive for use in applications where the fiber is exposed to a large radiation dose for a brief period of time but is expected to recover quickly.

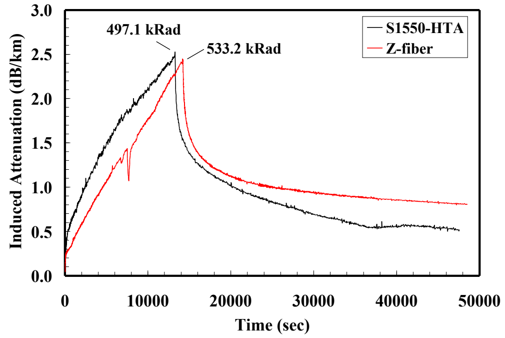

Fig. 5. Proton test data of S1550-HTA fiber.

Induced attenuation growth versus accumulated proton dose plots for the two fibers are shown in Fig. 6. S1550-HTA fiber with the higher NA (0.16) performs fairly well in comparison to Z-fiber® which has relatively smaller NA (0.12). For both the fibers, attenuation growth data can be represented well by the three-term "saturating exponentials" model described earlier. Solid lines in Fig. 6 represent best fit to the data. The best fit parameters are presented in Table 9. S1550-HTA shows a trend towards saturation while Z-fiber® does not indicate any such behavior. Using the data in Table 2 and Table 9, radiation induced-attenuation of S1550-HTA fiber at room temperature and to a total accumulated dose of 50 kRad is predicted to be 1.33 dB/km and 0.76 dB/km in γ- and proton radiation environments, respectively.

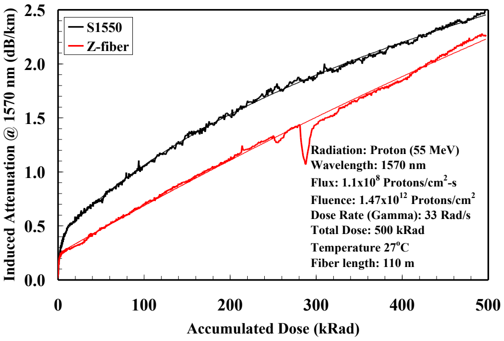

Fig. 6. Proton radiation data of S1550-HTA and Z-fiber®.

Table 9. Fitting parameters of the fibers in proton radiation environment.

Fiber	Parameter
S1550-HTA	a_1: 0.391; τ_1: 2.581
	a_2: 576; τ_2: 128.95
	a_3: 4.04; τ_3: 1070.4
Z-Fiber®	a_1: 0.242; τ_1: .958
	a_2: 0.139; τ_2: 126.30
	a_3: 8.07; τ_3: 1805.5

4. CONCLUSIONS

Experimental data on γ- and proton-radiation hardness/tolerance of several of the Nufern fibers that include SM, MM and PM versions which find application in LEO satellites have been presented. It is hoped that this information will alleviate some of the concerns regarding paucity of such valuable data that is so desperately needed by the designers of satellites and their payloads. Nufern is undertaking this activity on a continuous basis and more data would be forth coming in future.

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