Radiation Effects Expected for Fiber Laser/Amplifier Rare Earth Doped Optical Fiber

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1.0 Introduction

Fiber lasers are still considered an emerging technology because at the system level there exists no harsh environmental qualification data that is available to the public. Some vendors such as IPG claim to have thermal and vibration data on their units but NASA still needs to conduct validation analysis and testing to insure the technology will function as expected under harsh environmental conditions. In most cases the known failure modes of these systems can be approached and validated in the way other COTS photonics devices have been validated in the past for reliable functionality[1-2].

In general fiber lasers are of great interest due to the fact that they are primarily intrinsic systems, in that the majority of components that make up a fiber amplifier system are linked with optical fiber. Typically these systems consist of: rare earth doped amplifier fiber, pump diodes, bragg gratings, isolators, thermal controllers, and a fiber coupling mechanism (packaging technique varies). Failure modes created from the contamination of bulk optics in a vacuum environment don't plague the functionality of such a system provided no bulk optical components exist to enable this mechanism. Most designs avoid bulk optical components for example, bragg gratings intrinsic to the optical fiber core are used as filters and mirrors [3] in place of their bulk optic counterparts that are used in solid state laser systems. In additional, these gratings have been tested at very high dose rates for usage in nuclear plant facilities [4] and low dose rate environments have shown to be fairly stable.[5]

2.0 Generally Known Failure Modes

As with pumped solid state lasers, alignment of the fiber and components is crucial not only because of performance but because of the high powers used and the damage that can be imparted if the power ever becomes concentrated in a small area (focused too tightly and out of alignment). Double clad rare earth doped fiber that has a fluorine doped outer cladding is commonly used in current designs of high power amplifiers [6-7]. At large pump power levels above 100 watts, fluorine doped double clad fiber can be damaged as a result of misalignments and the performance of the fiber laser alignment can be validated through vibration and thermal testing. The potential degradation mode of fiber delamination of the double clad fiber can be validated through thermal cycling while monitoring optical performance parameters. Detectable degradation to the optical signal could indicate immediately, the beginning of delamination and thermally cycling the fiber will provide an effective method of further inducing the stress of the material mismatch. If any delamination occurs it should be more pronounced at the end faces where the mechanical stresses are at the highest and this can be validated through visual inspection after testing. In addition, other questions arise regarding the radiation sensitivity of this and other rare earth doped optical fibers used to amplify the source signal. There is some published data available however, as in most cases the dose rates, total dose, and dopants in the fiber all vary from experiment to experiment making a direct comparison a challenge. Presented here is a summary of some available data relevant to the usage of Erbium and Ytterbium doped optical fiber and the conclusions to speculate what the expected performance of these amplifier fibers will be in a space flight environment.

3.0 Radiation Effects

In general radiation sensitivity of optical fiber is largely dependent on the dopants used in the preform from which the fiber is manufactured.[8] This is also true for rare earth doped optical fiber. Radiation exposure induces color centers which affect the performance of the amplifier fiber by decreasing the small signal gain through absorption of the pump signal and the amplified signal is absorbed which decreases the output power. [9] The type and amount of dopants used in the fiber will dominate these effects. Typical dopants used are: Erbium, Ytterbium, Aluminum, Phosphorus, and Germanium. Aluminum is used for gain flattening and Germanium is used to raise the index of refraction. While Phosphorus is used to raise the index of the core, Fluorine and Boron are used to lower the index of the cladding. The dopants that are used to increase the index of refraction in the core of the amplifier fiber have a very large influence on the radiation susceptibility.[10] Another consideration for radiation induced effects is the wavelength of operation and the temperature of operation. It is well known that most optical fibers have larger absorptions at shorter wavelengths. This is also true when using pump sources at shorter wavelength. At colder temperatures the thermal annealing of the trapped charges can not occur while at higher temperatures the thermal annealing enables the trapped charges to be released. Also it is important to note that radiation induced attenuation will be higher when using lower wavelengths for the pump source.

3.1 Fiber Dopants

Greater Aluminum content in the core will increase the radiation induced effects in Erbium doped optical fiber. Several studies show this effect. One study shows that by altering the Aluminum content, the radiation induced darkening can be increased by an order of magnitude.[11] In this study published by H. Henshel et al., two optical fibers that contained almost the same amounts of Yb and P_2O_5, but very different amounts of Al_2O_3 were found to perform very different when exposed to the same dose rate and total dose conditions. Table 1 summarizes these results.

Table 1: From Reference 11, Summary of Results Comparing Two Yb-doped Fibers

Rare Earth Optical Fiber	Yb (mol %)	Al_2O_3 (mol %)	P_2O_5 (mol %)	TID	Radiation Induced Attenuation
1*	0.13	1.0	1.2	14 Krads	1 dB/m
2	0.18	4.2	0.9	14 Krads	12 dB/m

*Fiber 1 also contains 5.0 mol% of Germanium

Table 1 test conducted at 180 rads/min, 830 nm OTDR method used for monitoring under ambient conditions.

The testing was conducted at a dose rate of 180 rads/min which is 5 orders of magnitude larger than typical mission average dose rates. From past experimentation, reducing the dose rate by 2 to 3 orders of magnitude can reduce the radiation induced effects by 1 order of magnitude for germanium-doped multimode fiber up to the same total dose [8].

From the results of a study done in 1994 by C. Fukuda et al., where two fibers of identical Er content (0.1 %wt) but differing Al content (one at 1.0 %wt and the other at 3.0 %wt) were tested, there was an increase in the radiation sensitivity of the fiber that had slightly larger Al content. The high dose rate data was used to extrapolate to 100 Krads at a lower dose rate and the results were that the fiber containing 2% more by weight of Al experienced an increase in attenuation of 0.5 dB/m from that of the fiber with less Al.[12]

To better understand the effects of Erbium content as opposed to Aluminum, two studies were conducted on the Lucent Technologies, HE980 and HG980 that had large differences in Er content [13-14]. They performed nearly the same when exposed to the same conditions. The results from reference 13 are summarized in Table 2.

Table 2: Summary of Sensitivity Results Comparing Two Er-doped Fibers [13]

Rare Earth Doped Optical Fiber	Er Content	Al (%mol wt)	Ge (%mol wt)	Sensitivity 980 nm (dB/m Krad)	Sensitivity 1300 nm (dB/m Krad)	Sensitivity 1550 nm (dB/m Krad)
HE980	$4.5\ 10^{24}\ /m^3$	12	20	.013	.0041	.0025
HG980	$1.6\ 10^{25}\ /m^3$	10	23	.012	.0038	No data

Conducted at 84 rads/min up to 50 Krads for 3 meters of fiber under ambient conditions.

This data implies that for large changes in Erbium, little change exists in the radiation sensitivity, atleast among these candidates. This is in sharp contrast to what has been established about Al content. Another observation is how different the fibers perform at different wavelengths and the behavior illustrated here is very typical of optical fiber in general. The difference in sensitivity is an order of magnitude when comparing the radiation induced attenuation at 980 nm and at 1300 nm. In the study conducted by G.M Williams et al [14], data at high dose rates was used to extrapolate to lower dose rates using the power growth law method for prediction [15]. The extrapolation not only gives predictions at low dose rates that are very close to typical average dose rates for GSFC projects but also shows that these fibers exhibit a saturation behavior between a range of dose rates. The results of this data set and extrapolation values as graphed in the reference are in Table 3.

Table 3: Summary of Extrapolated Radiation Induced Attenuation for the HE980

Wavelength	Total Dose	Attenuation
980 nm	200 Krads	1.50 dB/m
1300 nm	200 Krads	0.25 dB/m
1550 nm	200 Krads	0.10 dB/m

Extrapolation dose rate of .038 rads/min used with ambient conditions.

Once again the order of magnitude change in radiation induced attenuation is apparent when changing the wavelength from 980 nm to the near IR wavelengths. In Table 4 the extrapolation parameters are used to recalculate the expected attenuation at low dose rates for a total dose of 200 and 100 Krads. For typical GSFC missions 100 Krads has been established as the total dose maximum for electronic systems and in general, most radiation hardened electronics are not specified as “rad hard” above 100 Krads. Therefore, if the maximum total dose becomes larger than 100 Krads, other system failures from the electronic components will dominate. When comparing the results in Table 4 to the results in Table 3, it is obvious that the calculated values are more conservative. The values of sensitivity used to make these calculations are also higher than that of reference 13. In making predictions it would be prudent to use the higher more conservative estimate of radiation sensitivity represented in Table 4.

Table 4: Calculated Expected Radiation Induced Attenuation for HE980

Wavelength	Total Dose	Attenuation
980 nm	200 Krads	1.56 dB/m
980 nm	100 Krads	**0.91 dB/m**
1300 nm	200 Krads	0.38 dB/m
1300 nm	100 Krads	**0.26 dB/m**
1550 nm	200 Krads	0.24 dB/m
1550 nm	100 Krads	**0.14 dB/m**

Values are based on sensitivity extrapolation model [15]

The values in Table 4 can be considered representative of typical commercial Erbium doped optical fiber radiation sensitivity during low dose rate exposure up to 100 Krads at 25 ºC. The fact that the sensitivity is at times twice that of what is represented in reference 13 can be attributed to the difference in experimental methods as well as the variation caused by testing of optical fiber from a different lot.

Also established in the studies mentioned above is a comparison of the proton versus gamma radiation induced attenuation. In both studies, there is data to indicate that the sensitivity of these optical fibers when exposed to the equivalent dose rate and total dose of protons in comparison to gamma rays is the same. Another important conclusion that can be made from the above studies as well as the studies performed on Yb doped optical fiber is that these fibers do exhibit a “saturation” behavior that is also seen in Germanium doped fiber. Saturation is reached when the annealing effects and the radiation induced trapped charges balance such that the radiation induced attenuation reaches a constant value for increasing dose while at a constant dose rate. If the temperature is raised or lowered this value will change to a lower value at higher temperatures and a much higher value at lower temperatures.

In accessing how sensitive these types of optical fibers are to radiation we can make a comparison to the typical performance of 100/140 micron core/cladding optical fiber that has been radiation tested at GSFC. In our studies we found performance for our commercial grade optical fiber is 1.7 10^{-4} dB/m at a dose rate of .01 rads/min, a wavelength of 1310 nm and a temperature of 25ºC.[2] In another study performed on step index 100/140 micron optical fiber at .032 rads/min, 50ºC, and 850 nm the extrapolated radiation induced attenuation to 100 Krads was 2.0 10^{-4} dB/m.[8]

To compare the performance of Yb doped fiber with Er-doped fiber, the data from Table 1 and the additional sensitivity data in reference [11] can be compared to the low dose rate data in Table 4. If we use the best performing Yb doped fiber from Table 1 we can calculate for a low dose rate the radiation induced attenuation at 100Krads. For this calculation we are assuming that the extrapolation values will be useful over a range that includes a dose rate of .04 rads/min as in the values calculated in Table 4. Therefore using this assumption, the radiation induced attenuation at 100 Krads is .45 dB/m for the better performing Yb-doped optical fiber. To make the comparison to an Erbium doped fiber we use the data for the HE980 in Table 4. However, the closest we can get to comparing wavelengths is by using the available data at 980 nm since no data exists at 830 nm as does exist for the Yb-doped fiber. Using the data from Table 4 that results from monitoring the Erbium-doped fiber at 980 nm the resulting radiation induced attenuation is .91 dB/m for 100 Krads. The values for radiation induced attenuation for both the Er-doped and Yb-doped optical fibers are very similar.

Finally, to get a sense of how other types of rare earth doped fibers perform, reference 11 can be used, since it also contains sensitivity data on Lanthanum doped optical fiber. The worst and best performer from this group of seven fibers manufactured by Lucent Technologies, Denmark are listed in Table 5.

Table 5: Best and Worst Lanthanum-doped Radiation Induced Attenuation Performance [11]

La (mol %)	Al_2O_3 (mol %)t	Total Dose	Wavelength	Atten.
1.8	8.0	100 Krad	830 nm	9.3 dB/m
2.0	6.0	100 Krad	830 nm	24.6 dB/m

From Table 5 it is evident that Lanthanum doped fiber contains large amounts of Aluminum but also is extremely sensitive to radiation induced effects as compared to both the Yb-doped and Er-doped candidates.

4.0 Conclusions

The data available provides some insight into how different dopants will affect the radiation induced attenuation of typical optical fibers for fiber amplifier systems. Presented here was also the data that establishes that these fibers perform similarly to other types of commercial non rare earth types of optical fiber in that the sensitivity increases at lower wavelengths, these fibers exhibit a saturation behavior, and that they perform similarly during gamma and proton testing.

Ultimately, the radiation induced performance will need to be verified based on the actual environment expected for the mission. Table 6 shows typical values used for the average total dose and dose rate for a few GSFC missions specified for the fiber optic systems aboard.

Table 6: Summary of Recent GSFC Mission Average Radiation Expectations

Program	Total Dose	Ave. Dose Rate	Duration
EO-1	15 Krad	.04 rads/min	10 years
GLAS	100 Krad	.04 rads/min	5 year
MLA	30 Krad	.011 rads/min	8 year (5 year ave)

In some cases the average dose rate is not based on scaling the total dose by the mission duration.

This indicates that using a dose rate of .04 rads/min is adequate for general speculation as a start. However, if the space craft hardware will require heaters or any other type of radioisotope sources such as required for Cassini, than other types of radiation environmental parameters need to be considered and used for testing purposes for a full characterization and technology assessment.

This summary was intended to give a sense of expected performance and compare commercially available components, however, this is just a brief summary of a few

publications and there exist many more. In addition, a variety of testing is being conducted presently to enable this technology for non NASA space flight usage. In addition, the technology continues to be refined by vendors involved in these studies for the space flight environment.
For updates on this report and other reports please see the website misspiggy.gsfc.nasa.gov/photonics

5.0 References

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