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RADIATION TOLERANT PASSIVE AND ACTIVE OPTICAL FIBER PRODUCTS FOR USE IN SPACE ENVIRONMENTS

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ABSTRACT

This paper reports the radiation performance results of several new product types designed for high radiation environments. The products tested include radiation hardened highly birefringent (HiBi) passive products for polarised applications and radiation tolerant active erbium doped fiber products for amplifiers.

Radiation hardened, short beatlength HiBi fiber products have been developed for high accuracy polarisation maintaining (PM) gyros and sensors at both 1310nm and 1550nm operation in the space environment. The fibers have been tested up to 5kGy (500krad) – levels which could be expected in extreme, extra-terrestrial space environments. Results show a consistently low Radiation Induced Attenuation (RIA) of <7dB/km at 5kGy, giving a RIA value of 1.37×10^{-2} dB/km/krad at 1550nm for this product range.

Radiation tolerant EDF AstroGain™ fibers are intended for use in multichannel amplifiers in optical inter-satellite communications. The structure of the fibers have been designed to deliver an accelerated recovery of radiation damage through photo-annealing using only the residual energy already available in an amplifier using a 980nm pumping regime. These products have been tested up to 200Gy (20krad) – levels which can be expected in Earth orbit environments over a 20-30 mission lifetime. Results show up to 100% recovery under continuous use for dose rates of 0.11rad/hr. It has also been demonstrated through analysis of the optical spectral output that this effect reverses the gain tilt, or spectral narrowing, induced by radiation damage through the C and L band. These combined fiber characteristics allow performance stability of the amplifier over the lifetime of the space mission.

I. INTRODUCTION

The space environment is one of extremes and rapid variability. Even within the confines of earth orbit, a spacecraft can encounter various radiation environments, with different particle types and intensities. Such high energy particles can be harmful to both humans and equipment, therefore a great deal of focus has been put into modelling the expected orbital dose rates, using software such as OMERE 2.0 [1,2]. For example, in Geostationary Orbit (GEO), the typical total dose that a spacecraft's systems will receive is approximately 137Gy over a 20 year mission (6.85Gy/yr), if sitting behind 10mm of aluminium shielding. For a Low Earth Orbit (LEO), the total dose over the same 20 year period would be under 66Gy (3.28Gy/yr) [1].

Fiber optic sensors, gyroscopes and amplifiers are becoming ever more prominent in the space industry. There is therefore a growing need for a range of radiation hardened optical fibers suitable for space environments. For example, with the emergence of microsatellites there is an increasing opportunity for space qualified Fiber Optic Gyroscopes (FOGs) [3]. Such gyroscopes are used for attitude control of a spacecraft; an extremely important system to ensure that the correct pointing and orientation of a satellite is accurately maintained over the life of a mission. The high accuracy, high reliability and low weight of FOGs make them very well suited to space applications, but such products must also be able to maintain this performance in the high radiation environment of space.

Radiation damage to a fiber generally causes the creation of point defects, as well as further damaging of pre-existing defects inherent in the fiber structure. The modification and creation of point defects results in changes to the energy level structure of the fiber, such that photons travelling through the fiber are absorbed by defects, causing increased attenuation – so called Radiation Induced Attenuation (RIA).

In most cases, an optical fiber is predominantly Silica with dopants added to create a raised refractive index core to form the waveguide. In passive fibers, the dopant added to the core is typically Ge, whilst in active fibers for optical amplification, the core composition is more complex and may contain numerous additional passive dopants (e.g. Aluminium) as well as the active rare-earth dopant (e.g. Erbium).

A Polarisation Maintaining (PM) fiber uses doped regions (typically doped with Boron) in the fiber cladding to create an axis of increased stress across the core. The result is a differential in refractive index, known as birefringence, of one orthogonal axis to the other. A high birefringence (HiBi) is key to separating the eigenstates of the polarisation modes, preventing cross-coupling from one mode to the other and hence preserving the polarisation state.

Different fiber dopants have different contributions to the RIA and due care must be taken when considering fiber composition suitable for space environments. The poor RIA performance of Phosphorous doped fibers is well known [4-6]. Other dopants such as Al [6-8], Ge [4,6] and B [5] have also been found to show detrimental effects to fiber performance under the influence of radiation. As a result of this, a favourable fiber composition is that of a Pure Silica Core (PSC) fiber. Rather than raising the core refractive index by adding dopants such as Ge to the core region, PSC fibers create a core waveguide by decreasing the refractive index of the inner cladding, usually by doping with F. By carefully selecting the PSC composition [9], it is possible to achieve even stronger resistance to RIA than traditional Ge doped fibers.

Space based communications also has a growing need for radiation tolerant Erbium Doped Fiber Amplifiers (EDFAs). Traditional Erbium Doped Fiber (EDF) has generally been considered inappropriate for use in high radiation environments due to the poor response of their dopants to radiation. To combat this, the new range of AstroGain™ EDF uses a modified dopant structure which encourages a fast photo-annealing recovery of radiation induced point defects, which continually restores the fiber's performance as it is being used [10].

II. TEST METHODS

A. IRRADIATION OF PM FIBER SAMPLES

A Co^{60} γ-ray source was used to provide the effective radiation doses needed for this study. Previous work has shown such a method to be suitable for simulating the effects of ionising events [9]. In the case of the radiation tolerant PM HiBi fibers, 500m sample lengths pertaining to three HiBi fiber variants were tested. Each was placed into the radiation test chamber at 24°C and subjected one of three dose rates, 50, 250 and 500Gy/hr over a four hour irradiation period to reach a total dose of either 200, 1000 or 2000Gy respectively.

Additionally, a separate sample set of radiation tolerant HB1500G-RT fibers have also been tested up to a higher total dose of 5000Gy at a dose rate of 250 Gy/hr. Finally, for use as a comparative baseline, a standard set of non- radiation tolerant HiBi fibers were tested at a dose rate of 50Gy/hr up to a total dose of 200Gy. The attenuation of each sample was measured before and after the irradiation to provide an overall RIA.

B. ASTROGAIN™ EDF SAMPLES

Three AstroGain™ samples each of 100m in length were irradiated at 50Gy/hr to a total dose of 200Gy, after which they were kept at room temperature for one year in order to remove thermal annealing effects from the measurements. Each sample was then cut to a length equivalent to 80dB of 1531nm peak absorption and deployed into the EDFA configuration shown in Fig. 1 in order to measure their photo-annealing response to a standard pump regime in the 980nm region [10].

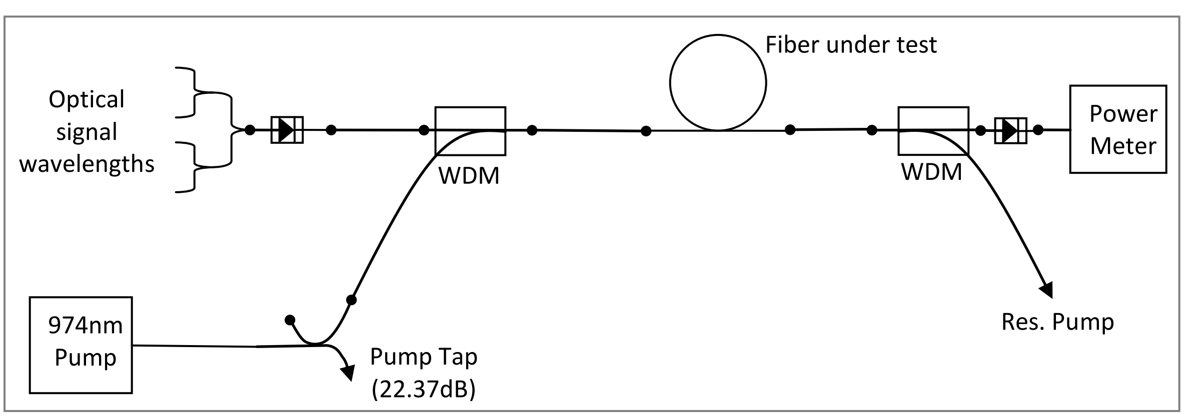

Fig. 1. Single pump EDFA photo-anneal set up

The EDFA setup was seeded over four channels: 1536.61nm, 1541.35nm, 1550.92nm and 1552.52nm and pumped continuously over several days at 974nm with a pump power of 175mW at the fiber input. The EDFA output was actively monitored over this period to deduce the level of photo-annealing recovery of radiation damage simply from the effect of the EDFA pump source. The output recovery was then extrapolated to a full mission duration of 20 years using a power curve fit in keeping with kinetic models of radiation damage [8,11].

The absorption and emission spectra of the AstroGain™ EDF samples were also measured using a straightforward cutback technique, before and after irradiation and again after the photo-annealing period. This would show how the spectral gain characteristics of the fiber changed throughout the process of irradiation and subsequent photo-annealing.

As with all these tests, the method of using high dose rate over short test periods is considered a worst case in comparison to the true space environment and mission duration. For the case of the active AstroGain™ EDF in particular, all of the radiation damage is done before the pump source is applied and therefore no pump induced photo-annealing can occur during this crucial period.

Studies have also shown that an equivalent total dose applied at a high dose rate over a short period will result in more damage than that from a lower dose rate [8, 11-13]. For the dose rates used, the samples were in fact given roughly the same effective total dose of a 30 year duration mission in GEO, or 60 years in LEO, but in a period of just 4 hours.

III. RESULTS AND DISCUSSION

A. RADIATION TOLERANT PM FIBER

Table 1 shows the RIA results from the first sample set of differing radiation tolerant fiber variants, which were irradiated up to a total dose of 200, 1000 and 2000Gy. From these measurements, it can be seen that the HB1500G-RT composition provides the most resistance to radiation damage over these test conditions.

A sample set of HB1500G-RT fiber was therefore tested further up to a total dose of 5000Gy. The results from these tests can be seen in table 2 for two selected wavelengths of 1310nm and 1550nm. A plot of the RIA across the full operational wavelength range can also be seen in Fig. 2, which shows a very consistent performance across the three samples. The averages of these results suggest a RIA of 1.37×10^{-2} dB/km/krad at 1550nm and 1.70×10^{-2} dB/km/krad at 1310nm.

Table 1. RIA measurements of three radiation tolerant HiBi variants for differing dose rates and total dose [6].

Fiber Type	**Total Dose (Gy)**	200	1000	2000
	Dose Rate (Gy/hr)	50	250	500
	RIA at 1550nm:	**(dB/km)**	**(dB/km)**	**(dB/km)**
HB1500G/033		1.55	2.85	6.89
HB1500G-RT		0.62	2.00	3.46
HB1500G/SB-001		0.33	3.52	5.23

Table 2. RIA measurements of HB1500G-RT after a total dose of 5000 Gy at a dose rate of 250Gy/hr.

HB1500G-RT Sample #	**RIA at 1310nm (dB/km)**	**RIA at 1550nm (dB/km)**
1	8.90	6.95
2	8.11	6.81
3	8.52	6.76

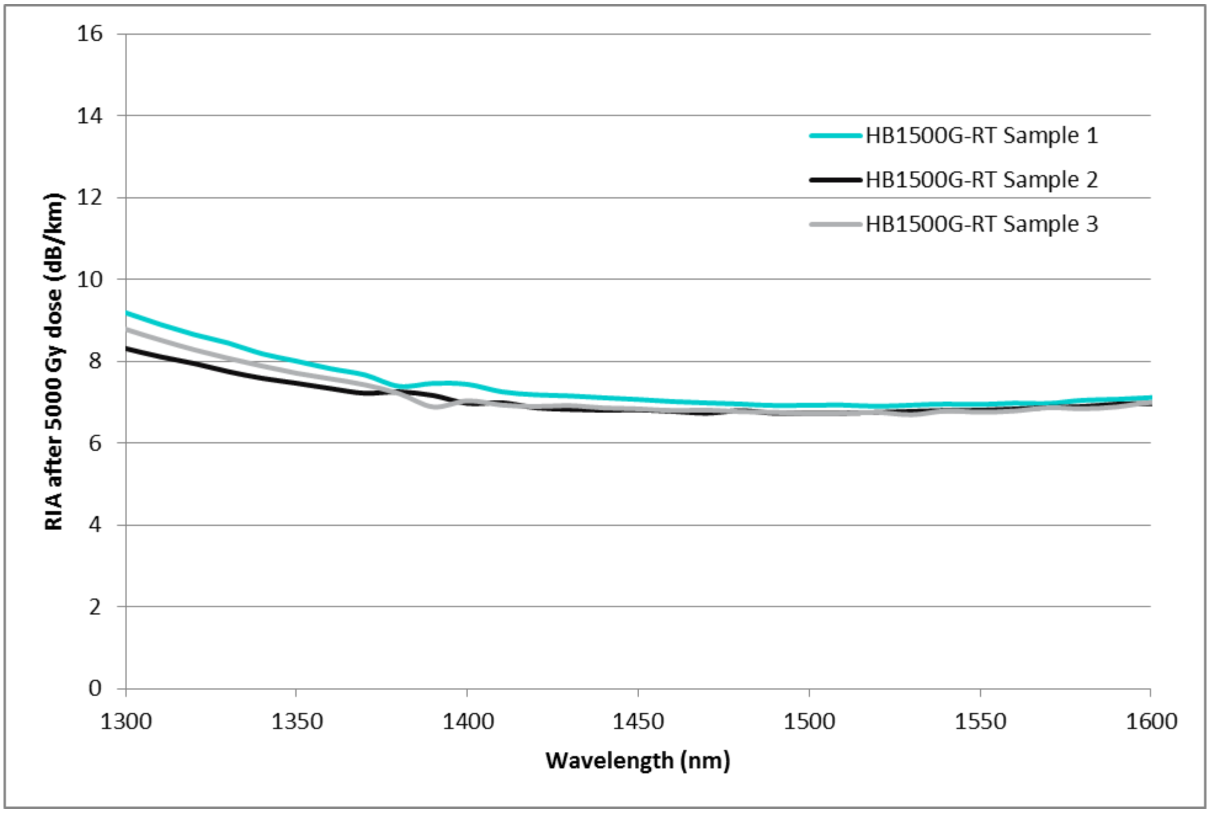

Fig. 2. RIA over operational wavelength range of HB1500G-RT samples after a total dose of 5000Gy.

B. STANDARD PM FIBER (NON-RADIATION TOLERANT)

Table 3 shows the RIA results of a selection of standard PM fibers after being irradiated with 200Gy at a dose rate of 50Gy/hr. A comparison of these results to the relative figures in Table 1 clearly show that the RIA in the radiation tolerant PM samples are 2 orders of magnitude below those of standard PM fiber composition. Even so, the standard PM fiber results in table 3 still show significant improvement compared to the previously reported radiation tolerance in PM fibers [14].

Table 3. RIA measurements of standard PM fiber samples [6].

Sample #	Fiber Type	RIA at 1550nm (dB/km)
1	HB1500G	54
2	HB1500G	58
3	HB1500G	63
4	HB1500G-HI	84
5	HB1500G-HI	58

C. ASTROGAIN™ EDF RADIATION PERFORMANCE

The measured RIA of each of the three AstroGain™ samples can be found in table 4, along with information about each sample’s passive trivalent material composition density. Each sample has a unique ratio of several passive trivalent materials such as Aluminium. The results show that the 974nm pump induced photo-anneal recovery appears to be proportional to the trivalent material density of the fiber.

The third column shows the RIA after irradiation and a period of thermal annealing, but before any photo-annealing is applied. The RIA after seven days of pump induced photo-annealing recovery is then shown in column four along with the extrapolated recovery after 20 years in the fifth column. A 20 year duration has been used here as a worst case estimate of the time it would take for a system in geosynchronous orbit to accumulate the 200Gy level of irradiation that the samples have been subjected to in this study. Models actually suggest the level after 20 years to be a much lower 137Gy [1].

Table 4. RIA and photo-annealing results for AstroGain™ EDF samples

AstroGain™ Sample #	Trivalent material % (scaled to fiber A-3)	RIA pre-anneal (dB/km)	RIA post-anneal (dB/km)	% output recovery after 20 years
A-1	43%	120.8	32.2	88.1%
A-2	93%	251.6	112.4	90.9%
A-3	100%	624.6	292.6	100.6%

Fig. 3 illustrates the photo-annealing recovery for AstroGain™ sample A-3 in terms of the observed signal output of the fiber in an EDFA deployment against annealing duration. This signal output is normalised to the output of an equivalent length control sample of A-3 that has not been subjected to any radiation.

Whilst the A-3 fiber shows the most initial damage as a result of the irradiation, the curve fit also shows a complete recovery of its performance within a 20 year period of continuous operation. Depending on the particular application, however, the fiber may not be in operation as an amplifier continuously. In light of this, Fig. 4 plots the expected percentage recovery for levels of discontinuous operation.

The differing recovery rates of each of the fiber samples are clearly seen by the gradients of the curves in Fig. 4. The data also suggests that for an application where the fiber amplifier is to be active for 20% or more of a 20 year mission, sample A-3 will provide the best performance. For a mission where the amplifier has a duty cycle of less than 20%, however, A-1 is the most appropriate choice.

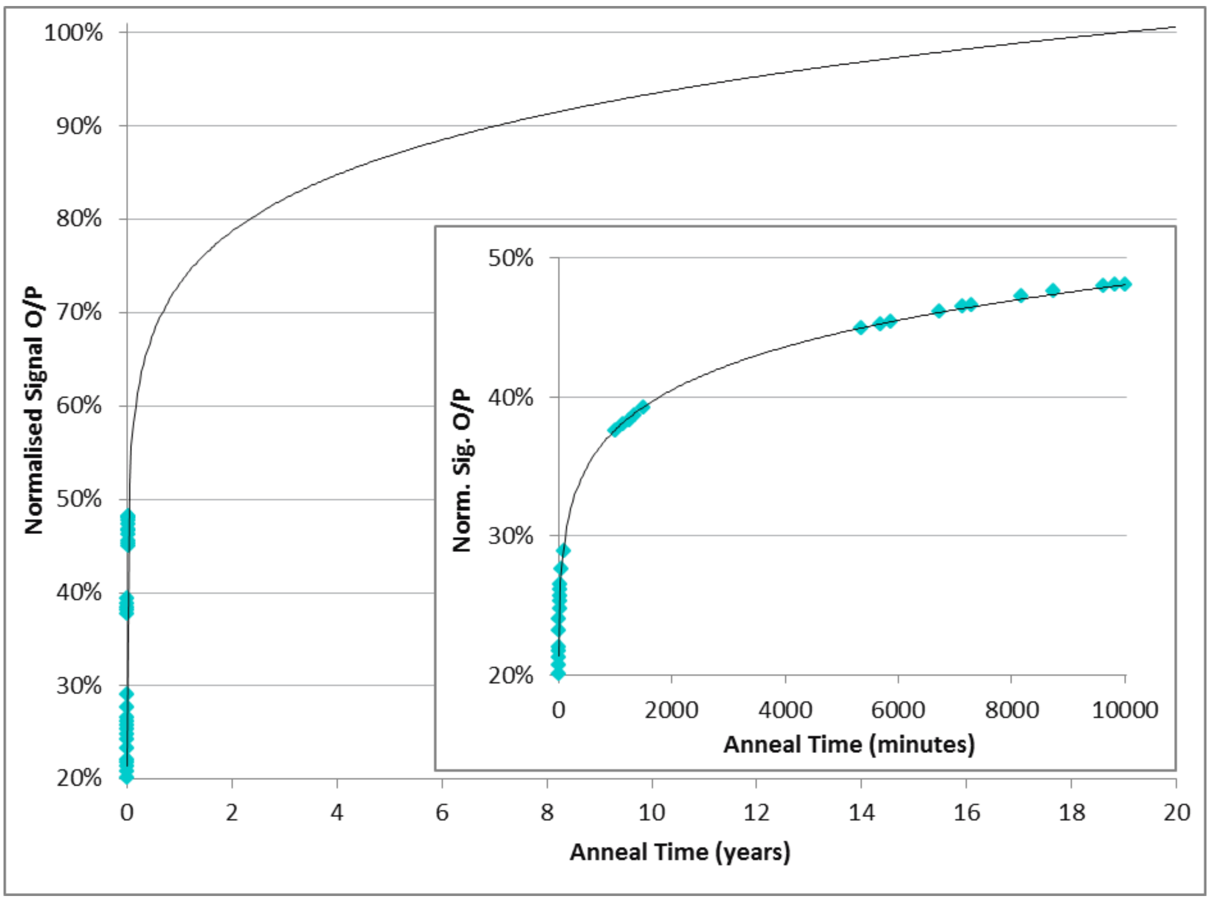

Fig 3. Recovering output over 20 years of annealing for A-3. Inset: close up of output vs. anneal time.

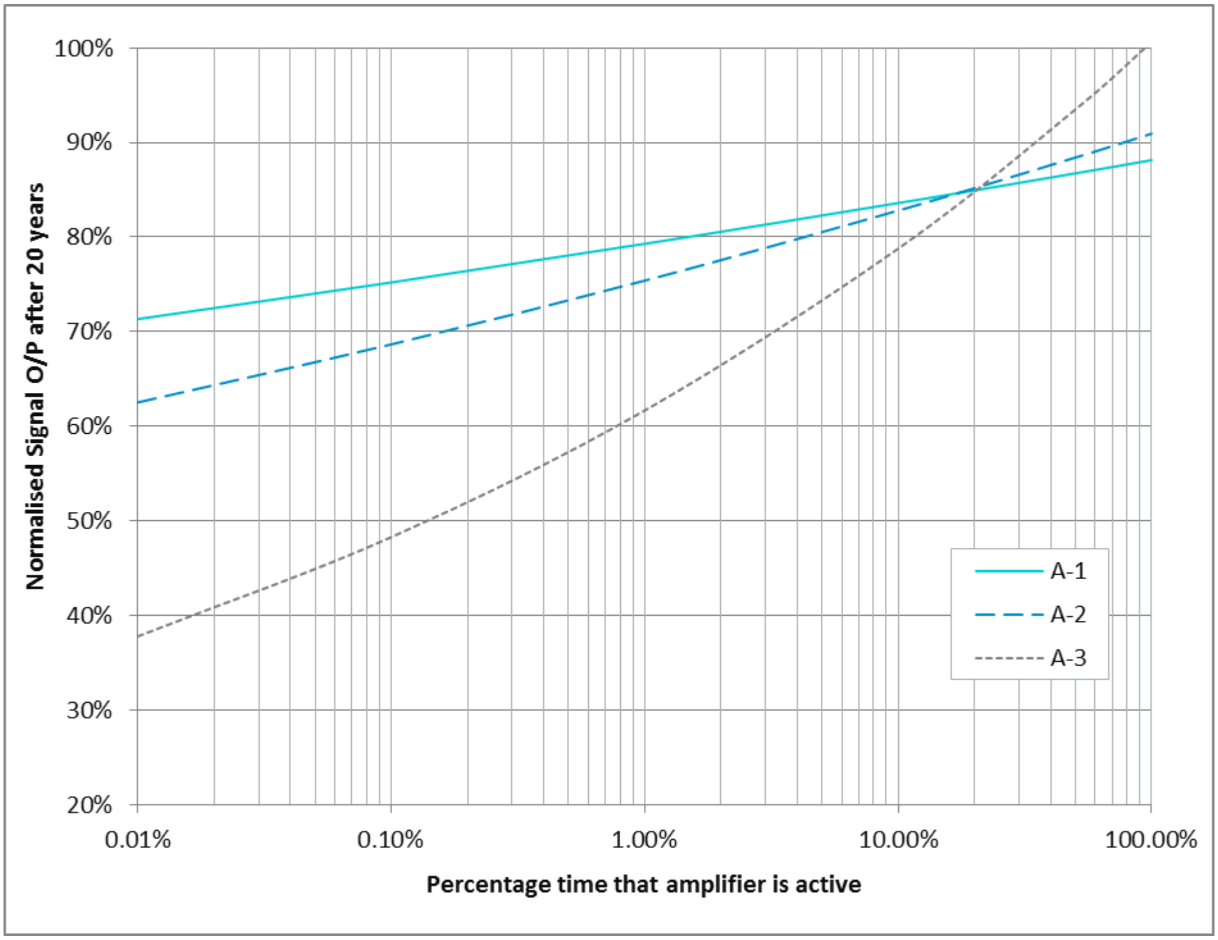

Fig. 4. Amplifier output recovery under discontinuous use

This study also investigated the effect of radiation damage on the spectral gain profile of the AstroGain™ EDF samples. Fig. 5 shows the measured gain spectrum of the A-3 sample (a) before any irradiation, (b) after being irradiated with the total dose of 200Gy and finally (c) after the seven day 974nm pump induced photo-anneal period. The results show that the radiation and resultant point defect creation appears to have the effect of narrowing the spectral bandwidth of the fiber. This is undesirable, especially for multichannel amplifiers that rely on a wide gain bandwidth and a stable flatness profile so that each wavelength channel receives a consistent amplification relative to the other data channels.

To combat this effect, the compositions of the AstroGain™ samples have also been designed to use the photo-annealing effect to recover their spectral bandwidth. This can also be seen in Fig. 5, where the spectrum after a seven day photo-annealing period shows clear recovery of bandwidth. The considerable recovery shown here from this short photo-annealing period would be achieved by a duty cycle of only 0.1% in a 20 year mission.

The spectral gain performance of these samples is seen to correlate well with the measured amplifier performance reported in Fig. 3. Applying the same accepted power curve fit [8,11] to the spectral recovery, the sample A-3 is also expected to fully recover its spectral shape and performance after a 20 year photo-annealing period. The results further suggest that even in these worst case test conditions, the fiber performance of A-3 can be fully and continuously maintained for an average dose rate of 0.11rad/hr – equivalent to 200Gy over 20 years. This is achieved by utilising an accelerated pump induced photo-annealing effect, simply using the energy from a 175mW 974nm pump source, which is already present in the EDFA system.

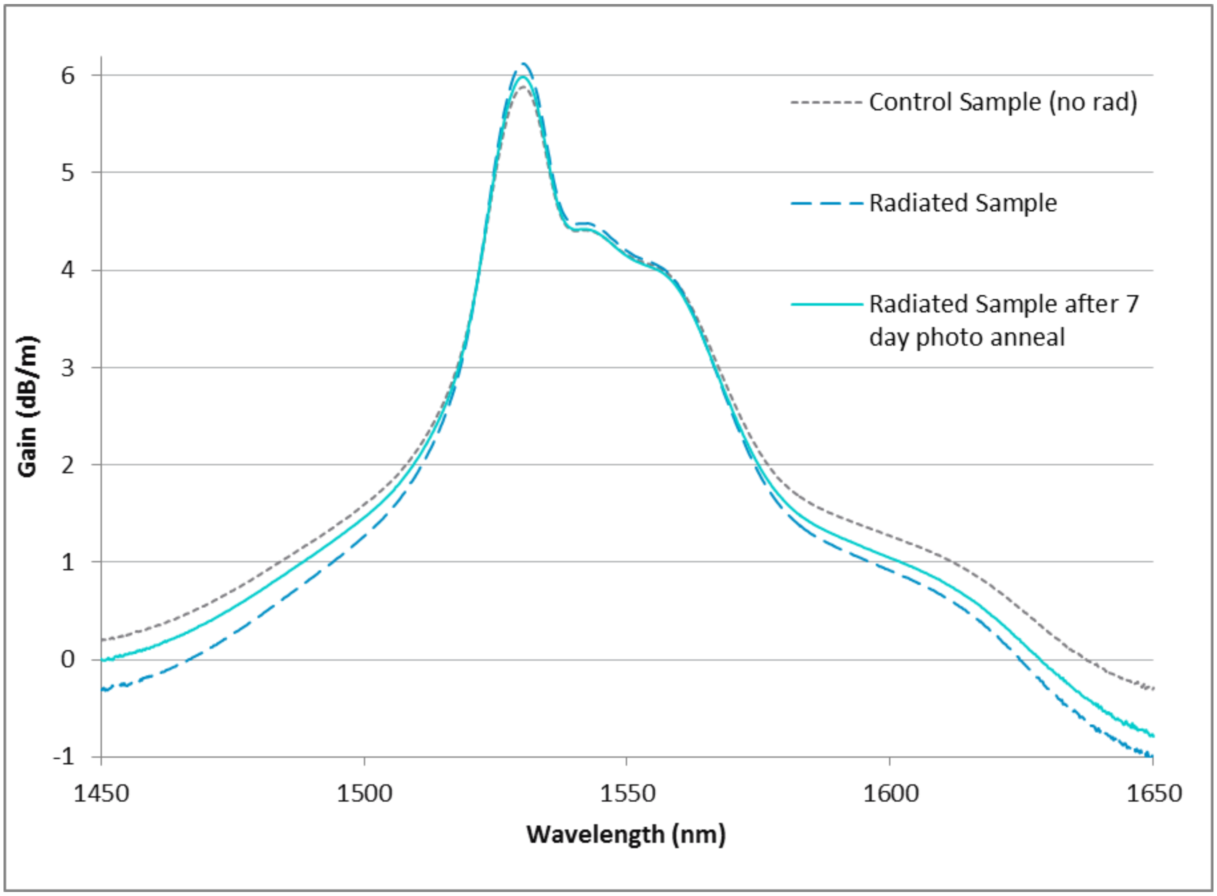

Fig. 5. A-3 fiber gain spectra before irradiation, after irradiation (200Gy) and after a 7 day photo anneal.

IV. CONCLUSION

RIA results from testing radiation tolerant, highly birefringent PM fibers have shown two orders of magnitude improvement over the radiation resistance of standard PM fibers for the same dose rate and total dose. After an effective dose of 5000Gy at a dose rate of 250Gy/hr, attenuation measurements of the Fibercore HB1500G-RT range have shown losses to be below 9dB/km at 1310nm and 7dB/km at 1550nm. This is equivalent to an overall RIA of 1.37×10^{-2} dB/km/krad at 1550nm or 1.70×10^{-2} dB/km/krad at 1310nm. The losses have been shown to be consistently low across the full operation wavelength range.

Radiation results of the AstroGain™ A-3 fiber sample have demonstrated up to a full recovery of amplifier performance as a result of photo-annealing by a single 974nm pump of 175mW. The unique fiber composition is seen to enhance the photo-annealing of point defect damage at this pump wavelength, maintaining a stable performance under continuous use for average dose rates to at least 0.11rad/hr. This dose rate is in excess of those typically seen in both GEO and LEO, 0.078rad/hr and 0.037rad/hr respectively [1]. As well as EDFA output, the spectral gain shape of the fiber is also maintained under these conditions.

A partial recovery can be expected under discontinuous use, however the composition of the A-1 sample can be utilised under these conditions to maximise the EDFA performance. The user can therefore select the most suitable fiber composition depending on the expected usage of the EDFA system. As a result of this study, Fibercore have released two product variants: AG980H for high duty cycle and AG980L for low duty cycle space applications. AG980H is based upon the composition of the A-3 sample in this study, whereas AG980L is based upon A-1.

The radiation damage reported here can be considered a worst case, given that the test methods subjected the fiber samples to dose rates many orders of magnitude great than would be experienced in a space environment. In the case of the radiation tolerant HiBi range especially, the total radiation dose is also well in excess of that expected for a typical mission duration. The RIA experienced in these environments would therefore be less than the levels reported in this study and the real time recovery rate of the AstroGain™ EDF would be further improved upon the values reported here.

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