

Application-Driven Selection of Polarization-Maintaining Fibers for Fiber Optic Gyroscopes: From Terrestrial to Space-Grade Radiation Performance and Beyond

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ABSTRACT

The radiation tolerance of polarization-maintaining (PM) fibers remains a critical parameter for the performance of fiber optic gyroscopes in space. While space-grade PM fibers are widely used, the relevance of developing next-generation of deep-space-grade (DSG) fibers remains an open question. This work compares the performances of terrestrial-grade (TG) and space-grade (SG) PM fibers under X-rays up to 300 krad(SiO₂), with controlled variations in both dose rate and temperature of irradiation (-40 °C to 80 °C). Levels and kinetics of radiation-induced attenuation (RIA) are evaluated at 1550 nm to quantify its impact for typical FOG coil lengths. To investigate the needs for further radiation hardening strategy, a complementary study is performed on single-mode (SM) fibers with compositions comparable to PM fibers. Similar RIA behaviors are observed between SG PM fibers and their SM counterparts, indicating that the RIA is primarily governed by the core and cladding glass composition. Based on this result, a DSG SM fiber is used to estimate the achievable radiation hardness of next-generation fibers. However, due to structural differences between SM and PM fibers, careful consideration is required when extrapolating these results to DSG PM fibers for future spaceborne FOG systems. The results indicate that current SG PM fibers remain appropriate for most spaceborne FOG applications, whereas DSG approaches appear advantageous only for deep-space missions involving the higher cumulative doses, up to 1 Mrad(SiO₂).

Keywords: Polarization-maintaining fibers, Radiation-induced attenuation, Fiber optic gyroscopes, Radiation, Space applications, Dose rate effects, Single-mode fibers, Deep-space missions

1. INTRODUCTION

Over the past two decades, significant advances have improved the radiation tolerance of optical fibers, enabling their reliable use in spaceborne systems [1]. The development of radiation-hardened erbium-doped fiber sources [2], [3] and optimized polarization-maintaining [4] (PM) fibers has allowed fiber optic gyroscopes (FOGs) to be successfully qualified and integrated into space applications [5]. The Astrix family of Inertial Reference Units (IRUs), developed jointly by Exail and Airbus, relies on high-performance FOGs as core inertial sensors. These systems have undergone extensive ground qualification campaigns and are deployed across multiple space missions. Follow-up studies have analyzed long-term in-orbit telemetry and compared it with a one-year ultra-low dose-rate gamma irradiation campaign on Earth [4], [5], providing insight into long-term radiation-induced attenuation (RIA) behavior and strengthening the correlation between ground testing and in-flight performance. RIA in the fiber coil has been identified as the dominant degradation mechanism and the primary performance-limiting factor under irradiation.

RIA in silica-based optical fibers originates from the formation of point defects [6], whose generation and recombination mechanisms depend on both the glass composition and environmental conditions such as dose rate and temperature. Historically, most radiation-tolerant fibers used in space applications have relied on germanium-doped core waveguides, optimized to balance optical performance and radiation sensitivity. However, controlling the core composition alone is not sufficient to ensure radiation hardness. The overall response of the fiber also depends on the full fabrication process [7], [8], including cladding composition [9], and coating materials [10]. As a result, understanding the respective roles of material composition and technological parameters becomes essential when designing radiation-hardened optical fibers.

The appropriate radiation-hardness level for PM fibers is increasingly critical. The rapid growth of the New Space ecosystem promotes shorter development cycles and wider use of COTS components [11], [12], while ambitious long-

duration missions, including deep-space and Jovian programs, impose higher cumulative doses and longer operational lifetimes [13], [14]. Determining whether terrestrial-grade fibers suffice, whether space-grade designs offer an optimal balance, or whether enhanced radiation tolerance is required for specific mission profiles remains a key challenge for next-generation high-performance spaceborne FOG systems with long fiber coil lengths.

In this context, we investigate the radiation response of optical fibers intended for spaceborne FOG applications. A comparison is performed between terrestrial-grade (TG) and space-grade (SG) PM fibers in order to identify the key parameters governing RIA and to assess their relevance for representative mission scenarios. The question of whether further improvements beyond current space-grade technologies are required is then addressed through the investigation of a deep-space-grade (DSG) fiber. As no DSG PM fiber is currently available for evaluation, this study relies on a DSG single-mode fiber as a representative material platform for advanced radiation-hardening approaches. The objective is therefore not to compare SM and PM fibers directly, but to estimate the radiation hardness that can realistically be achieved through advanced glass compositions and manufacturing processes. A similar comparative approach was previously proposed by Kashaikin *et al.* [15], who investigated both PM and non-PM fibers with different core compositions to assess their suitability for long-term space applications. Building on this approach, the present work extends the comparison to terrestrial-, space-, and deep-space-grade fiber technologies and uses a deep-space-grade single-mode fiber as a proxy to estimate the achievable performance for future radiation-hardened PM fibers.

2. MATERIAL AND METHODS

Fiber Sample

The study focuses on fibers with different expected radiation tolerance levels, including TG, SG, and DSG technologies. The selected TG and SG PM fibers are representative of those currently used in fiber optic gyroscopes for terrestrial and space applications. Although both PM fibers rely on a germanium-doped silica core and exhibit comparable guiding properties, they are manufactured using different fabrication processes. In addition, a SG SM fiber with a similar core composition to the SG PM fiber was investigated to further analyze the impact of the PM structure on RIA. Finally, a DSG SM fiber based on a pure silica core was evaluated to assess the radiation tolerance achievable through advanced fiber compositions.

Table 1. Investigated optical fibers manufactured by Exail

Radiation tolerance	Fiber Name	Polarization maintaining	Core composition	NA
Terrestrial-Grade	BC019LS	TIGER	Ge	0.19
Space-Grade	PMG-1550-80-019-E	TIGER	Ge	0.19
Space-Grade	SM-1550-80-019	No	Ge	0.19
Deep-Space-Grade	RAD-SM-1550-014-HT	No	Pure silica	0.14

A brief consideration should first be given to the choice of using SM fibers instead of PM fibers to investigate radiation-induced attenuation behavior. The possibility of polarization-dependent RIA in PM fibers, resulting from their stress-applying structures (SAPs), has been investigated in several studies and recently reviewed in [16]. These studies aimed at determining whether the RIA differs between the slow and fast polarization axes due to the anisotropic structure induced by the SAPs. While some studies reported a measurable RIA anisotropy, with differences typically ranging from a few percent to several tens of percent depending on the irradiation conditions, other investigations observe no significant polarization dependence. The reported effects also appear strongly dependent on experimental parameters such as irradiation type, dose rate, temperature, and post-irradiation recovery conditions. In [15], Kashaikin *et al.* concluded that, based on their comparison, the RIA of birefringent optical fibers would not be higher than that of isotropic optical fibers. Therefore, although RIA anisotropy may affect the polarization-dependent performance of FOGs under specific conditions, previous studies suggest that the overall radiation sensitivity remains mainly governed by the glass composition and fiber manufacturing process, through their influence on defect generation mechanisms. Consequently, SM fibers with comparable or representative glass compositions can be considered relevant platforms for evaluating the intrinsic radiation response of PM fiber materials and assessing the potential benefit of advanced radiation-hardening strategies. In this work,

SM fibers are therefore used as a complementary approach to investigate material-related radiation effects, while acknowledging that validation on PM architectures would ultimately be required to fully assess their FOG applicability.

In the present study, a cumulative dose of approximately 100 krad(SiO₂) was considered as a representative reference value for a typical 10–15 years space mission. The temperature range investigated, from -40 °C to 80 °C, was selected to account for the thermal variations that may be experienced in space [15], [17]. Higher doses were also investigated to explore the behaviors of the different fiber technologies under more demanding radiation environments, representative of extended-duration or deep-space missions. Before describing the irradiation facilities used in this study, it is worth briefly discussing the relevance of X-ray and γ -ray irradiation for reproducing the space radiation environment encountered by optical fibers. The space radiation environment is inherently complex, consisting of a mixed field of energetic particles and electromagnetic radiation, whose relative contributions strongly depend on the mission profile, orbit, and operational conditions [18]. For silica-based optical fibers, however, the dominant radiation-induced degradation mechanism at space-relevant fluence levels is associated with ionization processes and the subsequent generation of radiation-induced defects. It has been established in the literature [9], [19], [20] that, at fluence levels representative of the space environment, the RIA of optical fibers is primarily governed by the total ionizing dose and is therefore largely insensitive to the radiation type (protons, γ -rays...) when considering an equivalent absorbed dose. Consequently, the mixed radiation environment encountered in space can be effectively reproduced, to first order, using photon sources providing either γ -rays or lower energy X-rays, provided that the dose deposited in the fiber core is properly considered.

Table 2. Investigated optical fiber manufactured by Exail

3. EXPERIMENTAL RESULTS

Influence of fiber composition and manufacturing process

In order to establish a reference framework for comparing the different fiber technologies, measurements were first performed under standard irradiation conditions at 25 °C and a dose rate of 14.4 krad/h using X-rays. These conditions correspond to a typical accelerated test configuration, allowing clear differentiation between the radiation responses of the investigated fibers. The corresponding results are presented in Figure 1. Several key insights can already be drawn from these measurements.

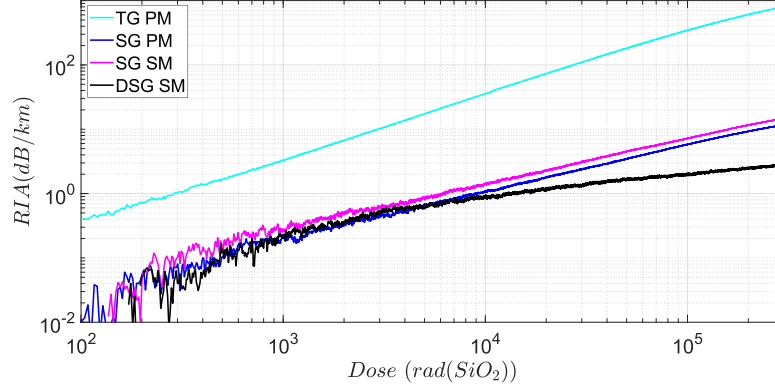


Figure 1. RIA at 1535 nm under X-ray irradiation at 14.4 krad/h and $T = 25^\circ\text{C}$ up to 300 krad for the different fibers listed in Table 2

First, although both terrestrial-grade and space-grade fibers rely on germanium-doped cores, their radiation responses differ significantly. The TG fiber exhibits a much higher infrared RIA ($800 \text{ dB} \cdot \text{km}^{-1}$ @ 300 krad), highlighting its lower radiation resistance compared to the SG counterpart ($13 \text{ dB} \cdot \text{km}^{-1}$ @ 300 krad). Since both fibers rely on Ge-doped cores, this result clearly demonstrates that radiation tolerance cannot be explained by core composition alone. Instead, it emphasizes the critical role of the overall manufacturing process in determining the final radiation response of the fiber, in agreement with the observations reported by [15].

The comparison between the SG PM and SG SM fibers shows very similar dose dependence and overall radiation-induced attenuation behavior under these irradiation conditions. A slightly higher RIA is nevertheless observed in the SG SM fiber, although the difference remains limited. This indicates that the presence of stress-applying parts does not significantly influence the overall RIA response. It should be noted, however, that the present measurements correspond to the overall fiber attenuation and do not resolve the differential RIA between the slow and fast polarization axes. Although this conclusion cannot be directly extended to the DSG SM fiber without further experimental verification, owing to its different core composition, the absence of a significant difference between the SG PM and SG SM fibers is consistent with the observations previously reported from the literature.

The DSG SM fiber investigated in this study exhibits an even lower RIA, reaching approximately $2.5 \text{ dB} \cdot \text{km}^{-1}$ at 300 krad under the same irradiation conditions which is five times lower than the SG PM. However, at lower dose levels below 10 krad, corresponding to the cumulative dose expected for approximately one year of operation in a typical space mission [15], the RIA of the DSG fiber remains comparable to SG PM. This indicates that the benefit of advanced radiation-hardening strategies becomes increasingly significant only at higher cumulative doses.

Temperature influence

Temperature is a key parameter influencing the radiation response of silica-based optical fibers, as it directly affects the balance between defect generation and thermally activated recombination processes. In space, the temperature experienced by optical components strongly depends on the mission profile, spacecraft architecture, and thermal control strategy. While fibers located inside thermally regulated spacecraft compartments typically experience temperatures ranging from approximately -20°C to $+40^\circ\text{C}$ during operation, wider excursions from -40°C to $+60^\circ\text{C}$ may occur during storage or non-operational phases. Even more extreme temperatures, from about -150°C to $+150^\circ\text{C}$, can be encountered by fibers installed in unheated external structures [17]. Although such extreme conditions are not representative of fiber optic

gyroscope coils, they illustrate the broad range of thermal environments encountered in space. Consequently, the influence of temperature was investigated over the range from $-40\text{ }^{\circ}\text{C}$ to $80\text{ }^{\circ}\text{C}$ under the irradiation conditions described in Table 2. The corresponding results are presented in Figure 2.

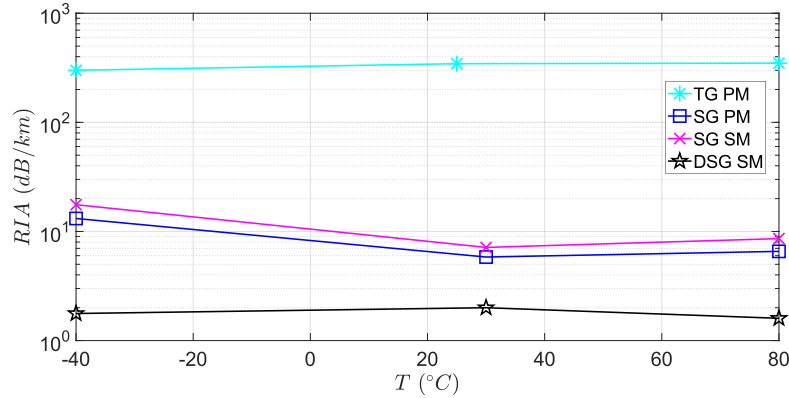


Figure 2. Radiation-induced attenuation at 1535 nm as a function of temperature under X-rays at 100 krad (14.4 krad/h) for the different fibers listed in Table 2.

Figure 2 shows that the TG PM fiber exhibits only a weak dependence of RIA on irradiation temperature over the investigated range. As a result, increasing the fiber temperature does not significantly reduce the accumulated attenuation, indicating that thermal bleaching cannot be considered an effective mitigation strategy for this fiber technology. In contrast, both the SG PM and SG SM fibers exhibit a pronounced increase in RIA when irradiated at $-40\text{ }^{\circ}\text{C}$, whereas similar attenuation levels are measured at room temperature and $80\text{ }^{\circ}\text{C}$. This behavior is characteristic of radiation-hardened Ge-doped fibers [23]. The radiation response of the DSG SM fiber does not exhibit any significant temperature dependence in our tested range. However, previous studies have shown that the radiation response of pure-silica-core fibers can be influenced by temperature under specific irradiation conditions, such as higher dose rates [24] or lower temperature regimes [15], [16]. It should also be noted that the radiation response of pure-silica-core fibers is strongly dependent on fabrication parameters, which can lead to significant variations in radiation sensitivity from one fiber to another [25] even with the same fabrication process [26].

Dose rate influence

Understanding the influence of dose rate on RIA is essential for space applications. While ground-based irradiation experiments are often performed under accelerated conditions at relatively high dose rates, most space environments are characterized by lower dose rates. The radiation-induced defects responsible for RIA can exhibit different generation and recovery kinetics, particularly when metastable defect populations are involved. At low dose rates, recombination processes can occur during irradiation, leading to a radiation response that may differ from accelerated ground-based tests. Therefore, ultra-low dose-rate experiments are required to properly assess the long-term behavior of optical fibers under space-relevant conditions. While some approaches rely on modeling the dose-rate dependence of RIA to extrapolate accelerated irradiation results toward space-relevant conditions [15], [27], the present work adopts a complementary experimental approach. The influence of dose rate is directly investigated over five orders of magnitude, combining accelerated X-ray irradiation with ultra-low dose-rate gamma irradiation. This approach provides direct insight into the evolution of RIA across a wide range of irradiation regimes, from laboratory testing conditions to values closer to those encountered in long-duration space missions. Due to experimental constraints related to space availability and the number of available measurement channels, the ultra-low dose-rate gamma irradiation campaign was performed only on the SG PM fiber. This fiber was selected as a representative space-grade technology currently used in spaceborne FOG applications.

Figure 3 presents the time evolution of the RIA measured at 1550 nm for three dose rates (2.2, 8.6, and 32 rad/h) for the SG PM fiber during the ongoing gamma irradiation campaign conducted over more than two years at PRESERVE. This irradiation campaign was previously analyzed in [4]; however, as the experiment has continued since this initial analysis, the results presented here have been updated to include the additional irradiation time and accumulated dose. The facility operates nearly continuously, with only occasional interruptions to allow access to the irradiation room. These short interruptions have a negligible impact on the overall experiment and are accounted for in the dose calculation using facility

log data. A few longer interruptions (greater than 12 hours), mainly due to planned shutdowns or source outages, were also recorded during the campaign and highlighted in blue in Figure 3.

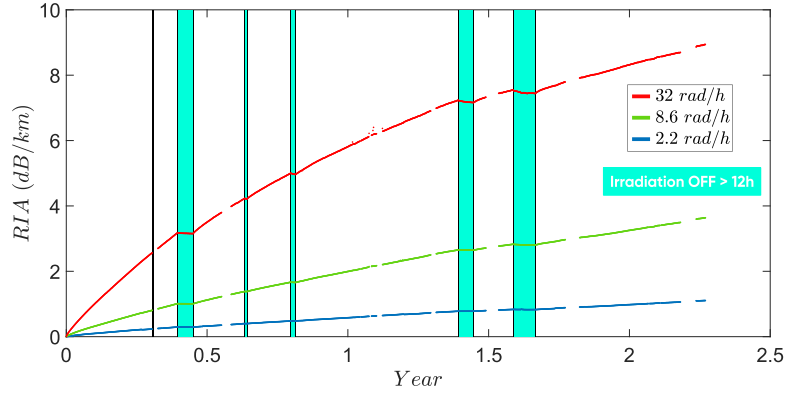


Figure 3. Time evolution of the RIA measured at 1550 nm for three dose rates (2.2, 8.6, and 32 rad/h) for the SG PM fiber during the ongoing gamma irradiation campaign conducted over more than two years at PRESERVE facility (Updated from [4])

Figure 4 shows that the variation of RIA measured at 30 krad remains limited, with a dispersion of approximately 8% between the different dose rates investigated during the gamma irradiation campaign. This limited variation suggests that no significant dose-rate dependence is observed over the considered range.

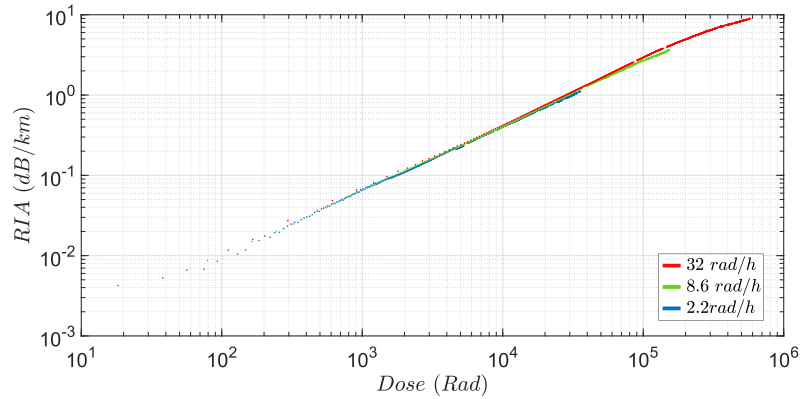


Figure 4. RIA measured at 1550 nm for three dose rates (2.2, 8.6, and 32 rad/h) versus dose for the SG PM fiber during the ongoing gamma irradiation campaign conducted over more than two years at PRESERVE (Updated from [4])

Figure 4 also reveals that the RIA evolution with accumulated dose does not follow a linear trend and can be described, at least up to 10^5 rad, by a power-law relationship. At higher doses, a deviation from this behavior is observed, suggesting a progressive saturation of the RIA. Nevertheless, for dose levels representative of most current space missions, the power-law approximation provides a good description of the RIA evolution.

Figure 5 provides a synthetic view of the RIA measured at 1535/1550 nm after a deposited dose of 30 krad as a function of dose rate for the different fibers listed in Table 2. Dose rates above 10^3 rad/h correspond to X-ray irradiation performed at LabHX, whereas dose rates below 10^2 rad/h were obtained through the ongoing gamma irradiation campaign at the PRESERVE facility. A first noteworthy result is the atypical behavior observed for the TG PM fiber, for which the RIA increases as the dose rate decreases. This trend suggests the involvement of metastable defects that do not contribute significantly to attenuation at 1550 nm but progressively convert into stable defects that absorb at this wavelength. Lower dose rates provide more time for this conversion process to occur during irradiation, resulting in a larger population of absorbing defects and therefore a higher RIA at a given accumulated dose. In contrast, the DSG SM fiber exhibits no significant dose-rate dependence over the investigated range. Previous studies have shown that pure-silica-core fibers may exhibit a strong dose-rate dependence at much higher dose rates [25], [28]. Under the irradiation conditions considered in this work, however, the observed RIA appears to be dominated by stable defect populations. This suggests that further

reducing the dose rate may not significantly decrease the RIA of this fiber. Finally, the SG PM and SG SM fibers exhibit the opposite behavior to the TG PM fiber, with RIA increasing as the dose rate increases. This observation is consistent with the presence of metastable defects that absorb at 1550 nm and progressively recombine. At high dose rates, these defects accumulate faster than they can recombine, leading to a larger measured RIA at a given dose during irradiation. At lower dose rates, recombination processes become more efficient and reduce the concentration of absorbing defects.

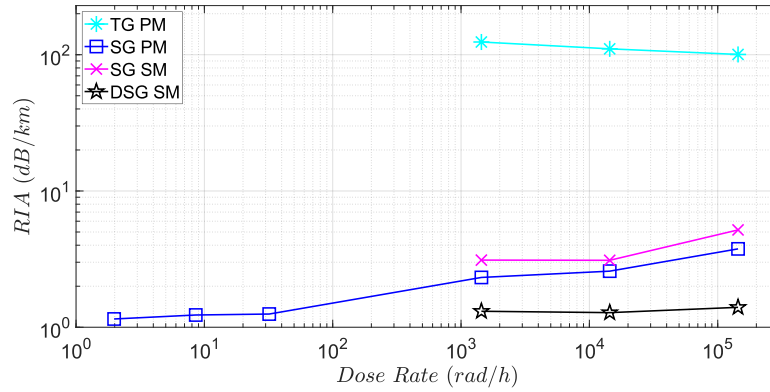


Figure 5. Radiation-induced attenuation at 1535/1550 nm at 30 krad as a function of dose rate for the different fiber listed in Table 2. Dose rates above 10^3 rad/h correspond to X-ray irradiation performed at LabHX, while dose rates below 10^2 rad/h are obtained under gamma irradiation at the PRESERVE facility.

The ultra-low-dose-rate measurements performed at the PRESERVE facility, shown in Figure 5, further demonstrate that the RIA of the SG PM fiber becomes comparable to that measured for the DSG SM fiber under accelerated irradiation conditions. Since space environments are characterized by very low dose rates, this result provides a plausible explanation for the excellent in-orbit performance previously reported for SG PM fibers. It also suggests that, despite their higher RIA during accelerated qualification tests, SG PM fibers remain particularly well suited for most current spaceborne FOG applications.

Influence of the mission parameters

The practical relevance of the radiation responses observed in this study ultimately depends on the targeted mission profile. As highlighted in the previous sections, environmental parameters such as temperature and dose rate can significantly influence the radiation response of an optical fiber. Consequently, assessing the suitability of a given fiber technology requires consideration of the actual conditions that will be encountered throughout the mission lifetime.

In particular, the thermal environment experienced by the fiber strongly depends on the spacecraft architecture, thermal control strategy, and location of the optical subsystem. Depending on the mission, optical fibers may operate under relatively stable and controlled temperatures or be subjected to much larger temperature excursions.

However, the most critical mission-dependent parameter remains the accumulated radiation dose. The total dose deposited in the fiber is governed by the surrounding radiation environment, which varies considerably depending on the region of space being explored. Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Orbit (GEO) [29], lunar surface missions [30] and Jovian exploration missions [13], [14] are all characterized by different particle spectra and radiation levels. As a result, the cumulative dose received by the fiber coil of a FOG can differ by several orders of magnitude from one mission to another, leading to very different requirements in terms of radiation tolerance. It should also be emphasized that the dose deposited in the fiber is not equal to the external radiation dose. Spacecraft structures provide a significant level of shielding and strongly modify the local radiation environment through both attenuation and secondary particle generation. Such shielding is essential for limiting the radiation exposure of onboard equipment and, in the case of crewed platforms such as the International Space Station (ISS), for maintaining a radiation environment compatible with long-duration human presence [31], [32]. Modern radiation environment simulation tools, such as OMERE [33] or SPENVIS [34], are commonly used to estimate the total ionizing dose associated with a given mission profile.

The results presented in the previous sections can then be used to assess the suitability of the investigated fiber technologies for the considered application. For a typical spaceborne FOG incorporating a fiber coil length of approximately 600 m, the use of the TG PM fiber does not appear to be a viable option. Even under low-dose-rate conditions, the measured RIA

remains sufficiently high to induce excessive losses. Indeed, Figure 5 shows that a RIA of $\sim 100 \text{ dB/km}$ is reached after only 30 krad under space-representative dose-rate conditions. For a 600 m coil, this corresponds to an additional loss of about 60 dB , incompatible with the optical power budget of a practical FOG. In contrast, the SG PM fiber appears particularly well suited to conventional space applications. The combined analysis of Figures 1 and 5 shows that this fiber exhibits a moderate RIA at low accumulated doses and benefits from a favourable dose-rate dependence under space-representative irradiation conditions. The excellent suitability of this technology for spaceborne FOGs is further supported by operational feedback from users of this fiber, notably through the Astrix family of fiber-optic gyroscopes [4].

The question therefore becomes whether the radiation tolerance offered by current SG PM fibers remains sufficient for future exploration missions. While current space missions typically expose optical fibers to cumulative doses of a few tens of krad, future exploration programs are expected to involve significantly more demanding radiation environments. Long-duration deep-space missions, solar missions, or missions operating within the radiation belts of Jupiter may expose optical subsystems to cumulative doses reaching several hundreds of krad or even the Mrad range. In this context, the reduced RIA exhibited by the DSG fiber becomes increasingly attractive. Figure 1 shows that, after a total dose of 300 krad , the DSG SM fiber exhibits a RIA of approximately 2.8 dB/km . For a typical 600 m FOG coil, this corresponds to an additional loss of only about 1.68 dB . By comparison, the SG PM fiber irradiated under the 32 rad/h gamma-ray conditions exhibits a RIA of 6.4 dB/km at the same dose level, corresponding to an excess loss of about 2 dB for the same coil length. The difference becomes increasingly significant as the dose accumulates. An additional benefit the DSG fiber may arise for missions involving prolonged operation at low temperatures. As shown in Figure 2, the RIA of the SG fibers increases significantly when the irradiation temperature decreases to -40°C , whereas the DSG exhibits a much weaker temperature dependence. Consequently, for spacecraft architectures in which the fiber coil may operate at low temperature and cannot be maintained within a tightly controlled thermal environment, the relative advantage of PSC-based technologies could become more pronounced than suggested by room-temperature comparisons alone. Consequently, while SG PM fibers appear fully adequate for most current spaceborne FOG applications, DSG technologies may offer valuable additional margin for future missions operating in particularly harsh radiation environments or requiring extended operational lifetimes.

4. CONCLUSION

This work investigated the radiation response of terrestrial-grade, space-grade, and deep-space-grade optical fibers for spaceborne fiber optic gyroscope applications. By combining accelerated X-ray irradiations with ultra-low-dose-rate gamma irradiations, the respective influences of manufacturing process, temperature, dose rate, and fiber composition were assessed. The results demonstrate that radiation tolerance cannot be explained by the sole fiber core composition and strongly depends on the overall manufacturing process. Temperature and dose-rate effects were shown to depend strongly on the investigated fiber. In particular, the favorable low-dose-rate behavior observed for SG fibers provides a consistent explanation for their demonstrated in-orbit performance in current spaceborne FOG systems. Finally, the mission-oriented analysis highlights that SG PM fibers remain fully adequate for most present-day space applications. However, the increasing radiation constraints associated with future deep-space and Jovian exploration missions may justify the development of DSG technologies, whose improved radiation tolerance can provide additional optical power margin at high accumulated doses. These results provide a practical framework for selecting the most appropriate fiber technology according to the targeted mission profile and radiation environment.

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