exail

Radiation-Hardened Optical Fibers

1 Introduction

Optical fibers offer many benefits compared to electrical cables and components, such a low intrusiveness and weight, low attenuation at telecommunication wavelengths, immunity to electromagnetic perturbations and a wide operating temperature range. For these reasons, optical fibers are increasingly employed in harsh environments for a wide range of applications including data transport, diagnostics and point or distributed sensing.

Harsh environments such as space, high-energy physics facilities, nuclear waste repositories, nuclear power plants or fusion experiments are characterized by the presence of ionizing and non-ionizing radiations. These constraints can significantly affect and, mostly, degrade the performances of standard optical fibers.

For more than a decade, Exail has cultivated a distinctive expertise in the design of specialty optical fibers for operation in harsh environments with extreme temperature and/or radiation level. Today, Exail offers an extensive portfolio, refined through extensive research and development efforts, supported by the best academic experts through the LabH6 joint laboratory. The LabH6 joint laboratory (shared with Hubert Curien Lab. at St-Etienne Univ.) specializes in the study of optical fibers and optical fiber-based sensors in harsh environments.

The present application note focuses on radiation-hardened optical fibers and reviews the key parameters for the selection of the most suitable fiber for a specific application.

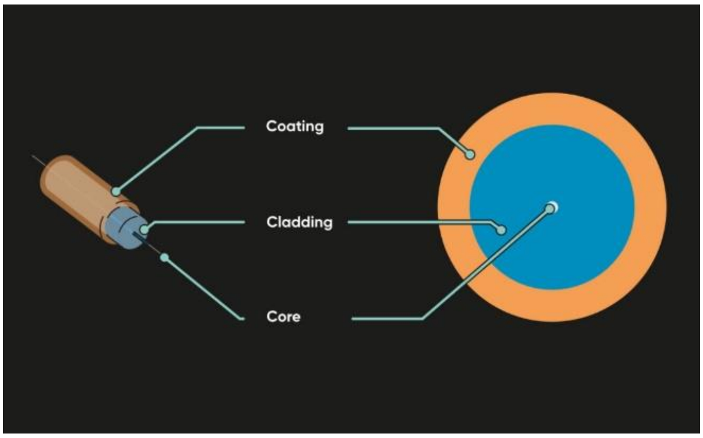

Figure 1 : Schematic representation of a singlemode fiber, showing the core, cladding, and coating.

2 Radiation effects on optical fibers

When employed in a radiative environment, four macroscopic effects can occur inside an optical fiber:

- Radiation-Induced Attenuation (**RIA**)
- Radiation-Induced Emission (**RIE**)
- Radiation-Induced Compaction (**RIC**)
- Radiation-Induced Refractive Index Change (**RIRIC**)

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In most cases, RIA is the most significant and detrimental effect and leads to a gradual darkening of the fiber core resulting in an increased attenuation of the propagating signal. RIA is due to the generation of radiation-induced point defects inside the optical fiber material. These point defects, also called color centers, can be seen as a local distortion of the atomic structure of the silica-based matrix and are associated with single or multiple gaussian optical absorption bands whose spectral characteristics depend on the atomic structure and concentration of the specific defect. As a result, the radiation induced attenuation is inherently wavelength dependent. The measured RIA corresponds to the sum of the contributions from all color centers. A comprehensive review of the various types of point defect and their main features can be found in [1] for different types of optical fibers.

Figure 2 : Visualization of Radiation Induced Attenuation (RIA) on glass irradiated by 6 MeV electrons at room temperature. From left to right: pristine glass, 600 Gy(SiO_2), 1 kGy(SiO_2), and 5 kGy(SiO_2), from [2].

The evolution of the RIA as a function of the accumulated dose depends on a variety of parameters, such as:

- The optical fiber composition, geometry, and manufacturing process (glass stoichiometry and impurities).
- The environmental conditions: nature of particles, radiation dose and dose-rate, temperature.
- The profile of use: operating wavelength and optical power level.
- Pre-treatments, such as hydrogenation or pre-irradiation.

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Because of this complexity, and despite extensive research and literature on the radiation hardness of optical fibers, no predictive models are today available to accurately estimate the RIA under given environmental conditions. Exail’s fibers are routinely measured under irradiation, but the irradiation conditions may not always be representative of the final environment. When possible, the best way to accurately estimate the RIA for a given environment remains to perform a test in similar conditions as those of the targeted application.

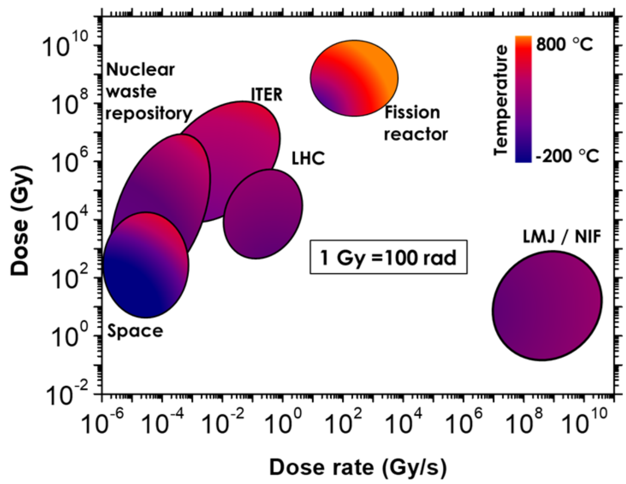

Figure 3 : Representation of different radiative environments, showing large variations of total ionizing dose (TID) and dose rate, courtesy of Prof. Sylvain Girard (Hubert Curien Lab.).

3 Mitigating RIA with Rad-Hard fibers

> **Radiation-hardened optical fibers**

Radiation hardened optical fibers are designed to mitigate the radiation induced attenuation and extends the fiber's lifetime in moderate to highly radiative environments. Most fiber applications in non-radiative environments can be transposed to radiative environments using radiation-hardened optical fibers which typically use a Pure Silica Core (PSC) or F-doped core. Radiation-hardened fibers typically exhibit low RIA of the order of ~10 dB/km at 1550 nm for a dose of a few hundred kGy(SiO_2), making them appropriate for high doses environments such as nuclear waste repositories, nuclear industry or high-energy physics facilities.

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Exail's radiation-hardened fibers are commonly used at the MGy level and have been investigated up to the GGy level and neutron fluences up to 10^{20} n/cm^2 for in-core applications in [3], [4], [5] and [6]. Exail's Rad-Hard fibers have been used in a variety of applications including temperature monitoring with FBGs [7], Raman distributed temperature sensing (RDTS) [8], nuclear core instrumentation [9], and plasma monitoring in fusion experiments [10].

While most Radiation-Hardened fibers rely on a Pure Silica Core (PSC) or Fluorine doped (F-doped) core, these designs in themselves do not provide any guarantee of good radiation resistance. Ultra-low loss singlemode fibers with Pure Silica Core developed for telecom applications were studied in [11] and showed a pristine loss before irradiation of just 0.16 dB/km at 1550 nm, better than traditional Germanium-doped fibers. Despite having a pure silica core, this fiber proved to be extremely sensitive to radiations with RIA levels up to 2000 dB/km at 1550 nm and 2 kGy(SiO_2). The extremely high RIA likely originates from dopants within the core and from the drawing conditions, both aspects being known to have a significant impact on the radiation response of an optical fiber.

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PSC fibers are often used to mitigate H_2 darkening in hydrogen-rich environments and are as such not always designed nor optimized in terms of radiation induced attenuation. In [3], the radiation response of a radiation resistant singlemode fiber from Exail (previously iXblue) is compared to two commercially available PSC fibers and a SMF28 germanium-doped fiber. Figure 4 illustrates that PSC fibers can have very different responses under radiation.

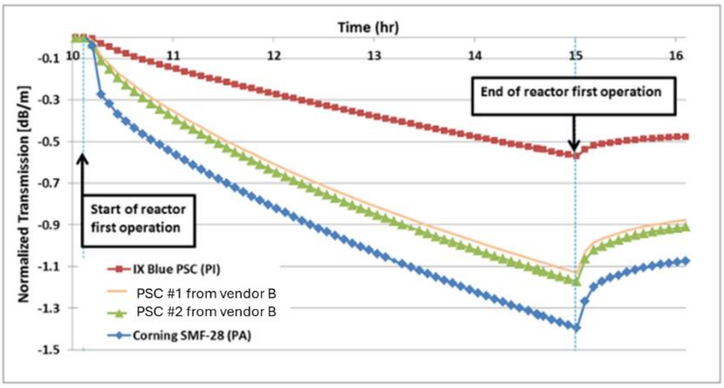

Figure 4 : Comparison of Exail's (previously iXblue) radiation-hardened fiber (in red) with 2 PSC fibers (in green and orange) and standard SMF28 fiber (in blue), from [3]. Values closer to 0 indicate a lower RIA and better radiation resistance.

Radiation-tolerant optical fibers

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For low to intermediate total ionizing doses and fiber lengths, so-called radiation-tolerant fibers with a Germanium-doped core can in some cases be a viable alternative to radiation-hardened fibers. Radiation-tolerant fibers can be employed for short data links in radiative environments with low accumulated doses, typically up to a few tens of kGy(SiO_2), such as space environment. RIA levels of 10 dB/km are typically attainted on radiation tolerant fibers for doses of the order of 10 kGy(SiO_2). Similarly to radiation-hardened fibers, the core composition and drawing conditions of radiation tolerant fibers are optimized to keep RIA levels to a minimum.

Radiation-tolerant fibers can be conveniently used as a lead fiber to connect radiation-hardened fiber located in a highly radiative area to a distant instrument deported in a non-radiative zone. Exail offers radiation-tolerant fibers matched to its radiation hardened fibers, ensuring low-splice loss.

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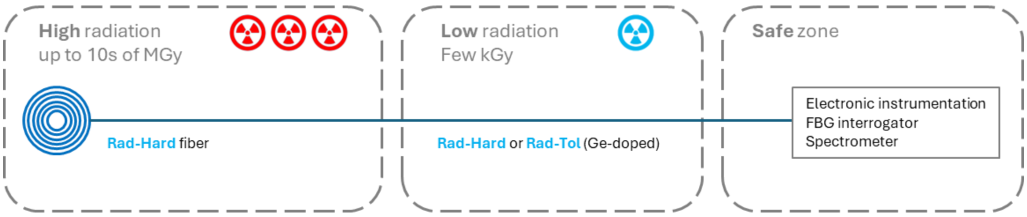

Figure 5 : Radiation-hardened fibers used in highly radiative environments and connected to electronic instrumentation through either a radiation-hardened or radiation-tolerant (Ge-doped) fiber.

Standard telecom fibers such as the Corning's SMF28 can be an appealing alternative to radiation-tolerant specialty optical fibers due to their lower cost. The radiation response of SMF28-like fibers have been studied under radiation for example in [12]. Telecom fibers are however usually only available with standard acrylate coating, limiting the operating temperature range to +85°C. In addition, given that the radiation response depends strongly on both the preform manufacturing process and drawing conditions, different fibers within the same SMF28 family (SMF28, SMF28e+, SMF28 ULL, SMF28 Ultra) are likely to behave differently under radiation.

4 Rad-Hard fiber selection

Exail provides a wide portfolio of singlemode and multimode radiation-hardened optical fibers. It is useful to consider the following points when looking for a radiation hardened fiber to narrow down the search to the most relevant fiber references:

- Singlemode or multimode fiber
- Operating wavelength, or wavelength range
- Total ionizing dose, dose rate and type of particles
- Continuous or intermittent irradiation
- Operating temperature

The optical properties and mechanical reliability are two key aspects discussed below.

4.1 Optical properties

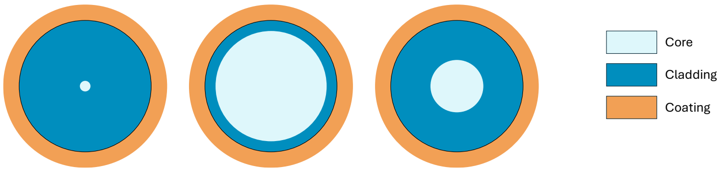

Figure 6 : Schematic representation of the 3 main geometries of optical fibers: singlemode (left), 105-125 µm step-index multimode (middle), and 50-125 µm graded-index multimode (right).

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- **Singlemode fibers**

Singlemode fibers have a very small core, typically ~8 µm, and offer low-loss operation around the design wavelength. Applications that require high bandwidth or FBGs mostly rely on singlemode fibers.

Exail offers several radiation-hardened singlemode fibers across the 900 - 1650 nm wavelength range. The fiber composition and drawing conditions are tailored to minimize the presence of precursor sites that could generate under radiation absorbing color centers within the operational wavelength range of the fiber.

Figure 8 and Figure 9 illustrate the wavelength and temperature dependence of the RIA measured on the IXF-RAD-SM-1550-014-HT fiber, a radiation hardened singlemode fiber designed for operation in the 1550 nm region. Color centers can also spontaneously recover or interact with dopants or other color centers with kinetics which are sensitive to temperature, making the RIA temperature dependent.

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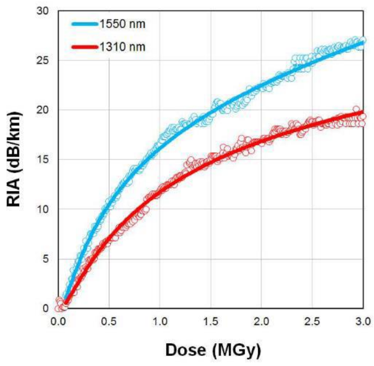

Figure 7 : In-line RIA measurement at 1310 nm and 1550 nm on the radiation-hardened singlemode fiber IXF-RAD-SM-1550-014-HT showing the growth kinetic and wavelength dependence [13].

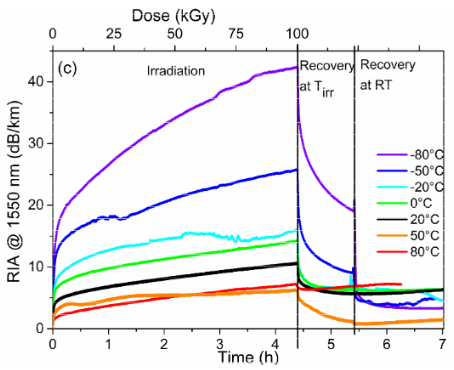

Figure 8 : In-line RIA measurement at different temperatures between -80°C and +80°C on the radiation-hardened singlemode fiber IXF-RAD-SM-1550-014-HT showing the growth kinetic and temperature dependence, from [14].

The recovery after irradiation, as shown in Figure 8, can play a significant role in environments with intermittent irradiation in maintaining good signal transmission.

> Step-index multimode fibers (MMSI)

Step-index multimode fibers have a much larger core diameter and operating wavelength range compared to singlemode fibers. The standard geometry has a Ø105 µm core within a Ø125 µm cladding, but larger core sizes such as Ø200 µm and Ø400 µm are also commonly used. Thanks to their large core size, MMSI fibers are particularly suited for applications such as diagnostic, spectroscopy, light collection, and power delivery.

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Step-index multimode fibers use a pure silica core (PSC) surrounded by a fluorine-doped cladding. Radiation-hardened versions rely on the same design but with a special attention to glass composition and drawing conditions to keep the RIA to a minimum. Radiation-hardened MMSI fibers, unlike standard telecom fibers, also have a specified RIA value and are tested under radiation after manufacturing.

The core composition of MMSI fibers can have different concentrations of OH-groups (Low-, Medium- and High-OH), affecting both the pristine (i.e. not irradiated) attenuation profile and RIA spectrum. Given the wavelength dependence of RIA and the broad operating range of multimode fibers, the variations of RIA as a function of wavelength should be carefully considered given the wavelength(s) of interest. Exail's radiation-hardened step-index multimode fibers have been studied under radiation across the 400 – 900 nm wavelength range in [15].

> Graded-index multimode fibers (MMGI)

Graded-index multimode fibers provide an improved mode delay and low temporal dispersion at the design wavelength. The large core size and low temporal distortion of Graded-index MM fibers make them particularly suited for temporal monitoring of ultrafast lasers. Standard graded-index multimode fibers have a Germanium-doped core and silica cladding, whereas radiation-hardened GI multimode fibers use a F-doped core with graded-index and a F-doped cladding.

MM Graded-Index (MMGI) can be employed for applications such as scientific onboard experiments on LEO/GEO satellites or temporal diagnostic of high-energy pulsed laser such as in CEA LMJ and LLNL NIF, as in [10].

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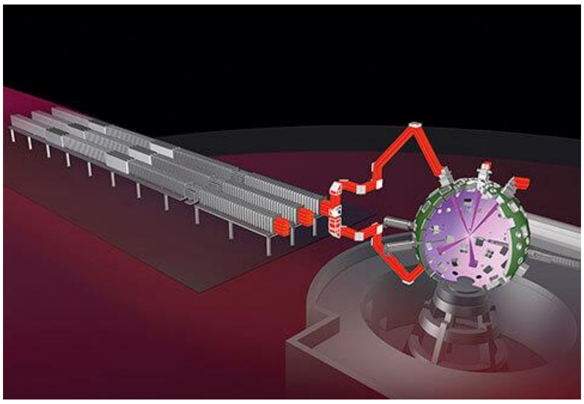

Figure 9 : Exail's radiation-hardened multimode graded-index fibers are key components for temporal monitoring of the 351 nm laser pulses at CEA LMJ and LLNL NIF inertial fusion facilities [16]. Read the full customer story in [17].

4.2 Coatings for harsh environments

The coating is a multi-purpose element, some of its key functions are to protect the mechanical integrity of the fiber, to shield the silica glass from chemicals, and to limit micro-bending. In addition to acrylate and high-temperature acrylate, Exail also offers polyimide and aluminum-coated fibers for operation under extreme temperature and/or radiation levels.

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Figure 10 : Exail offers several coatings for harsh environments, such as High-Temperature acrylate (left), polyimide (middle), and aluminum (right).

The table below summarizes the maximum operating temperature and geometrical form factor of the different coatings available.

	Maximum temperature	Øcoating (Ø125 µm cladding)
Acrylate	+85 °C	245 µm
HT Acrylate	+150 °C	245 µm
Polyimide	+300 °C	155 µm
Aluminum	+400 °C	170 µm

In addition to temperature, the mechanical reliability of an optical fiber exposed to radiations is another aspect where the coating plays a crucial role. Polyimide offers an improved radiation resistance compared to acrylate coatings, with failure probabilities and dynamic fatigue corrosion factor within the requirements of the IEC 60793-2-50 norm up to several MGy [13]. Metallic coatings such as aluminum have been shown in [5] to maintain their mechanical integrity up to the GGy level and should therefore be preferred for extreme radiation levels or when the operating temperature exceeds +300°C.

5 LabH6, a joint laboratory on Hardened Fibers

labH6

"The continuous effort to study the effects of radiations on silica fibers at a fundamental level directly translates into the continuous improvement of Exail's radiation-hardened fibers to minimize radiation induced attenuation."

The LabH6 Joint Laboratory was created between Exail and Hubert Curien Lab (CNRS/IOGS/St-Etienne Univ.) in 2019 to study optical fibers and optical fiber-based sensors in harsh environments, following more than a decade of collaboration through numerous funded projects and PhD programs.

The continuous effort to study the effects of radiations on silica fibers at a fundamental level directly translates into continuous improvement of Exail's radiation-hardened fibers to ever minimize radiation induced attenuation, at the forefront in the field. R&D efforts within the LabH6 joint laboratory are also opening the way to new developments in optical fibers for sensors in nuclear environment or for distributed radiation sensing, but also Fiber Bragg Grating for sensors in harsh environments.

6 Conclusions

The numerous advantages offered by optical fibers make them a good candidate for a variety of application in harsh environments, characterized by the presence of radiation, various types of gases and extreme temperatures. These environmental constraints can strongly impact, in a very complex way, the performances of the optical fibers in terms of transmission and mechanical resistance.

Because of this complexity, a tailor-made design approach is essential in the production of radiation-resistant optical fibers, involving the study of the composition of the silica-based glass and coating material to effectively mitigate the degradation. Radiation-hardened optical fibers, together with advanced polymer and metallic coatings, offer great designs choices to address applications with extreme temperature and/or radiation levels.

Exail's knowhow in specialty optical fibers includes all the key manufacturing steps, from MCVD preform manufacturing to fiber drawing and measurement under irradiation. Leveraging over a decade of experience on these subjects, Exail offers an extensive portfolio of radiation-hardened optical fibers tailored to meet the demands of diverse applications in challenging harsh environments.

7 References

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