Polyimide fibers

for harsh environments

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1 Introduction

This technical note discusses the use of polyimide-coated fiber for harsh environments with extreme temperatures and/or radiation levels, such as nuclear facilities, high energy physics laboratories, and space.

Figure 1 : different harsh environments with extreme temperatures and/or radiation levels.

While silica glass can intrinsically withstand temperatures well beyond +800°C, the coating that surrounds and protects the silica fiber degrades at a much lower operating temperature, making the coating the element that determines the maximum operating temperature of the fiber.

Leveraging 50+ years of continuous improvements made on standard telecom fibers, specialty optical fibers are now widely used in harsh environments for data transmission, sensing or diagnosis, leveraging the well-known benefits of optical fibers:

- Immunity to EM
- Lightweight and low volume
- Low loss
- High temperature resistance
- High bandwidth

Exail offers a wide range of passive (PM and non-PM) and active optical fibers with virtually unlimited design possibilities in terms of operating wavelength range, geometry, dopants and doping profile.

2 Coating materials and deposition

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. When selecting the coating material, the operating temperature is the first aspect to consider, but radiation resistance, outgassing, and hermeticity can also be critical factors to consider for certain applications.

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The coating is applied during the drawing process before the bare silica fiber touches any hard external surface. This ensures proper protection of the fiber before it touches the metallic drawing pulleys that pull the fiber at the bottom of the drawing tower.

For polymer coatings, the fiber goes through a bath of liquid polymer and exits through a die of calibrated diameter which sets the outer diameter of the coated fiber. The fiber is then cured in-line using a UV or thermal furnace to polymerize the coating. Depending on the coating material and recipe, several layers of coatings can be applied on top of each other to achieve the desired opto-mechanical characteristics. Each layer may have a different chemical composition and thickness.

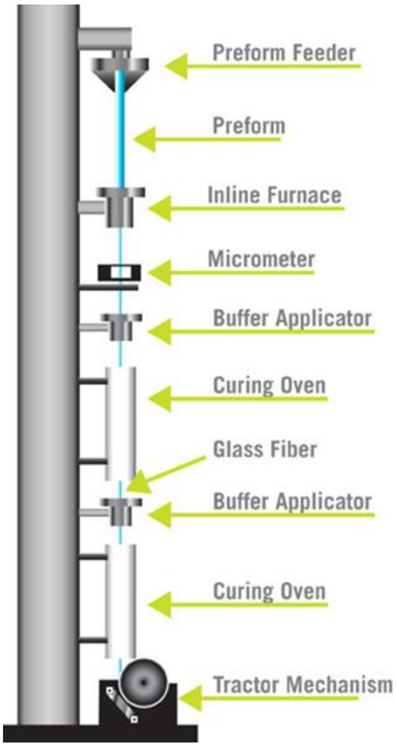

Figure 2 : schematic representation of the fiber drawing tower, with 2 buffer applicators and curing ovens placed one after another to apply 2 layers of coating.

The bare (uncoated) fiber diameter and the outside coating diameter are measured in-line during fiber drawing, together with many other drawing parameters. These parameters are monitored during the draw for process control and saved in a database for quality assurance and traceability.

On top of polyimide coating, Exail offers a wide range of polymer (including standard and high-temperature (HT) acrylate) and metallic (aluminum) coatings.

"On top of polyimide coating, Exail also offers standard and high-temperature (HT) acrylate, and metallic (aluminum) coatings"

Figure 3 : Exail offers several coatings for harsh environments, such as High-Temperature acrylate, polyimide, and aluminum.

The table below summarizes the maximum operating temperature and geometrical form factor of the different coatings available. Exail has started to add aluminum coatings to its portfolio in 2024, a direct result of the 3F2E project, a collaborative project that has sought to develop innovative metallic coatings for sensing applications in nuclear and other harsh environments.

	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

Table 1 : Typical maximum operating temperature and coating diameter depending on the coating material.

3 Polyimide-coated fibers

Polyimide has excellent temperature resistance making it suitable for operation from cryogenic temperatures up to +300°C. Exail is continuously expanding its portfolio of polyimide-coated singlemode and multimode fibers to better address applications in harsh environments.

"Polyimide has excellent temperature resistance making it suitable for operation from cryogenic temperatures up to +300°C"

Some of the key characteristics of polyimide-coated fibers are summarized below.

3.1 Mechanical strength

Exail's polyimide deposition process has undergone extensive mechanical qualification, including Weibull measurements, as shown in Figure 4. The dynamic fatigue coefficient n_d, as well as the stress values above which 15% and 50% of the samples fail mechanically ($\sigma_{0.15}$ and $\sigma_{0.50}$) exceed the GR-20-CORE Telcordia requirements.

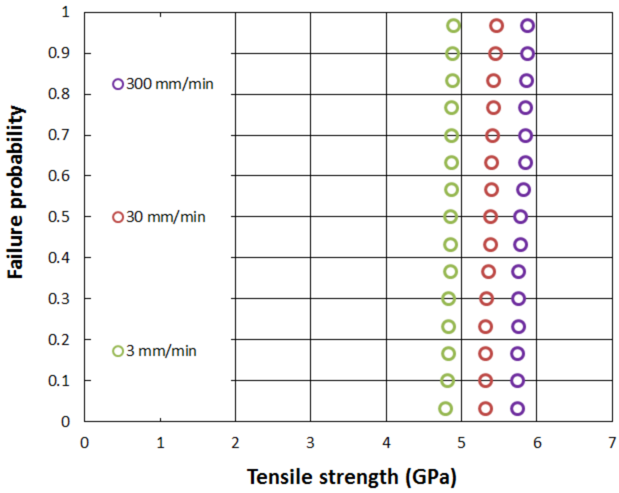

Figure 4 : Weibull measurements showing the failure probability as a function of tensile strength for different elongation rates. The dynamic fatigue coefficient was 24.6 (>18 to comply with the GR-20-CORE Telcordia norm)

3.2 Operating temperature range

The life-time prediction of a polyimide-coated fiber used at high temperature was performed using thermal gravimetric analysis. Samples of polyimide coated fibers were placed into a crucible of a thermo-balance and were subjected to a temperature ramp under air. The mass loss of the polyimide coating versus temperature curve is given in Figure 5.

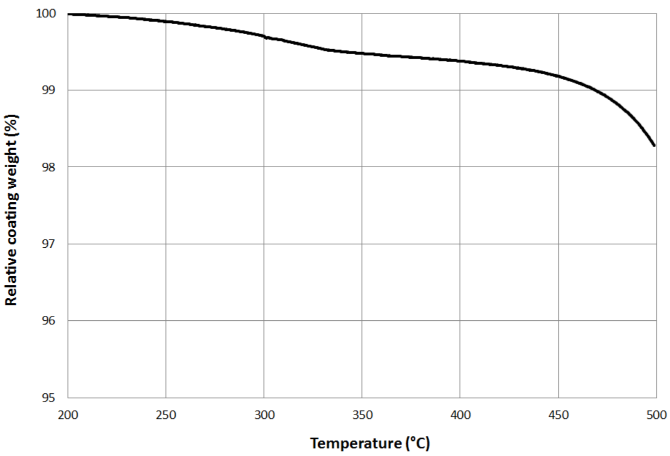

Figure 5 : mass loss measurements of a polyimide-coated fiber as a function of temperature.

The isothermal lifetime prediction in air can be extracted from the mass loss measurement, as shown in Figure 6 below:

- 15 years at +250 °C
- 1 year at +300 °C
- 1 month at +350 °C

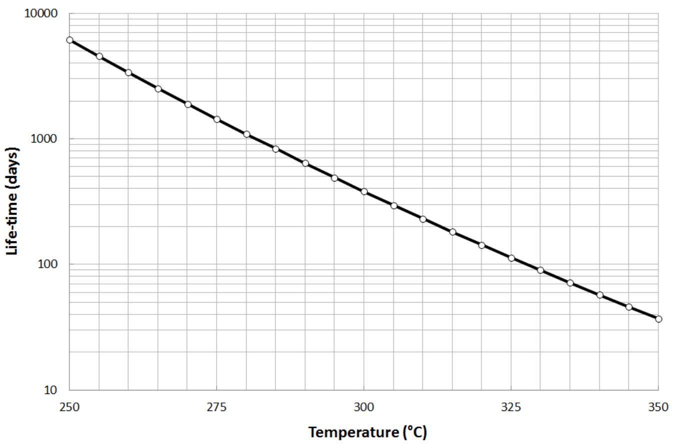

Figure 6 : isothermal lifetime prediction in air of a polyimide-coated fiber.

"Polyimide fibers have also been shown to work reliably under cryogenic temperature"

Polyimide fibers have also been shown to work reliably under cryogenic temperature. Exail's polyimide-coated fibers were qualified for fusion applications at liquid nitrogen temperature (77 K) in [1], and will be later on deployed at liquid hydrogen temperatures (20 K). The fiber should remain still once cooled down to cryogenic temperatures because of the brittle nature of polymers well below their glass transition temperature. Nevertheless, tests performed on polyimide coated fibers cooled at liquid nitrogen temperature for 24 hours showed no degradation of the optical transmission and excellent resistance to mechanical traction.

3.3 Geometrical considerations and coating quality

The coating diameter is measured in-line during the fiber draw. For a 125 µm cladding diameter, the external coating diameter is 155 ±5 µm. Figure 7 below shows a typical trace of how the coating diameter varies during the draw, with a stability of typically ±1 µm along the fiber length.

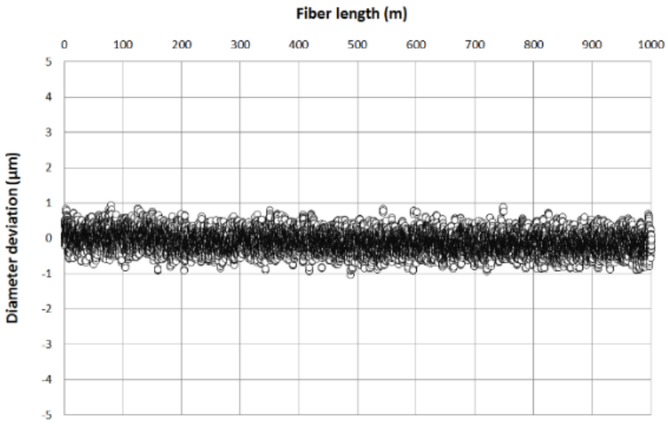

Figure 7 : Example trace showing the variation of coating diameter measured in-line during the fiber draw.

The stability of the coating diameter is particularly important for femtosecond FBG inscription where the FBG is inscribed directly through the polyimide coating. Concentricity errors or geometrical variations of the coating along the fiber length can affect the focusing of the femtosecond laser and the characteristics of the FBGs produced.

Similarly, femtosecond FBG inscription also requires a defect-free high-quality coating to achieve a high inscription yield and reach the FBG specifications consistently. Exail specialty optical fibers are manufactured with a strong focus on coating quality, achieved through rigorous cleanliness, optimized manufacturing processes, and dedicated monitoring instruments.

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Figure 8 : microscope view of a defect-free polyimide coated fiber.

3.4 Optical characteristics

The high Young modulus of polyimide makes it very resistant to abrasion but also more prone to transfer external stress to the silica fiber compared to dual layer acrylate coatings where a very soft primary layer with a Young modulus of 10 MPa or less is used.

For this reason, polyimide-coated fibers typically have slightly higher optical loss and are more sensitive to conditioning and microbending than acrylate-coated fibers

When working with FBG on polyimide fiber, special attention is needed because polyimide is known to absorb humidity and expand or contract as a result, a phenomenon which can visibly affect the Bragg wavelength of the underlying FBG.

3.5 Vacuum compatibility

The outgassing of a 100 m spool of polyimide-coated fiber manufactured by Exail was tested under thermal vacuum (+125°C, 24 hours, $P < 10^{-4}$ Pa). The measured Total Mass Loss (TML) and Collected Volatile Condensable Material (CVCM) comply with the recommendations of ECSS-Q-ST-70-02C, at <1 % and <0.1 % respectively. Contact your Exail's sales representative for more information about outgasing and vacuum compatibility.

3.6 Radiation resistance

Polyimide shows excellent radiation resistance and many publications have reported using Exail's polyimide fibers under high doses of Gamma and neutrons, up to 20 MGy in [2] and [3], and up to 130 MGy in [4] with a neutron fluence of 10^{19} n/cm². The combined effect of radiation and temperature has been studied in [5], showing no degradation of the mechanical strength after an irradiation up to 10 MGy at +90 °C.

3.7 Stripping polyimide

"Regular mechanical and thermal stripping tools designed for acrylate fibers should be avoided for polyimide fibers"

The hard nature of polyimide makes it more difficult to strip than acrylate-coated fibers. Regular mechanical and thermal stripping tools designed for acrylate fibers should be avoided for polyimide fibers.

The polyimide coating can be removed with mechanical, thermal, or chemical methods.

- **Mechanical**

Several mechanical stripping tools were specifically developed for polyimide fiber, including the PCS-100 (Fujikura) or the FWS-100 (Thorlabs). These mechanical strippers use a moving razor blade to peel the polyimide coating and strip the fiber of its coating in an automatic manner.

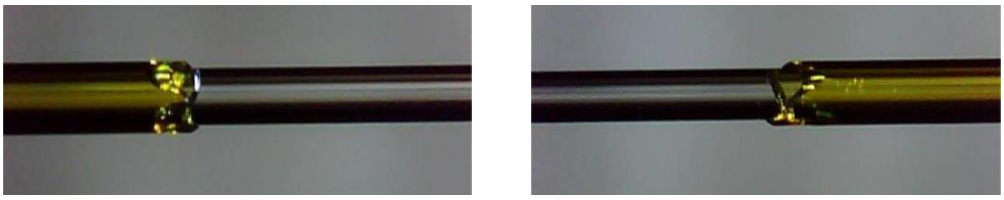


Figure 9 : images of a polyimide-fiber stripped with a PCS-100 mechanical stripper.

- **Thermal**

It is possible to use a CO2 laser, a flame from an oxygen/hydrogen torch, or an electric arc to expose the polyimide to temperature beyond which it degrades. These methods preserve the mechanical resistance of the silica fiber but are however relatively difficult to implement. For this reason, it remains relatively common to strip polyimide using the flame of a lighter, though this method is less reproductible and more prone to affect the mechanical characteristics of the silica fiber. To strip longer lengths, the polyimide fiber can be placed in an oven at a temperature beyond 600°C for 1 hour, or at a higher temperature to speed up the removal of the polyimide.

- **Chemical**

Chemical methods require appropriate precautions related to the use of hazardous chemicals. A bath of hot sulfuric acid (+100 °C) was shown to efficiently remove the polyimide coating in a couple of minutes.

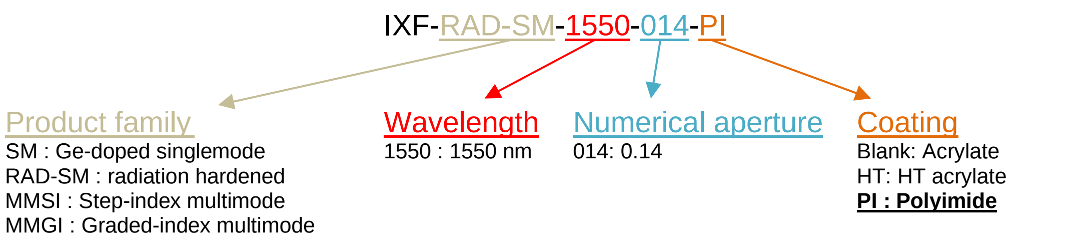
4 Exail's polyimide portfolio

"Exail manufactures different types of polyimide-coated fibers, including singlemode and multimode (step-index and graded-index) fibers"

Exail manufactures different types of polyimide-coated fibers, including singlemode and multimode (step-index and graded-index) fibers. The product code of polyimide-coated fibers ends with -PI, making it easy to identify the coating material from the fiber reference.

The 4 families of fibers that include polyimide-coated fibers are listed below:

- IXF-SM — Singlemode fibers, Ge-doped
- IXF-RAD-SM — Radiation-hardened singlemode fibers (Pure Silica Core)
- IXF-MMSI — Step-index multimode
- IXF-MMGI — Graded-index multimode



5 Conclusion

With over 20 years of expertise in the field of specialty optical fibers, Exail offers a wide range of polyimide-coated fibers for operation in harsh environments.
From standard commodity fiber for day-to-day manufacturing to highly specific fiber designs, Exail possess all the manufacturing tools and processes to address both large volume productions and custom developments.

Exail offers both singlemode and multimode polyimide-coated fibers with a strong focus on coating quality, ensuring both stable opto-mechanical fiber characteristics and high FBG inscription yields via femtosecond laser. Dense FBG arrays consisting of hundreds or thousands of FBGs can now be manufactured in a fully automated manner, putting even more emphasis on having a high-quality defect-free coating.

6 References

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