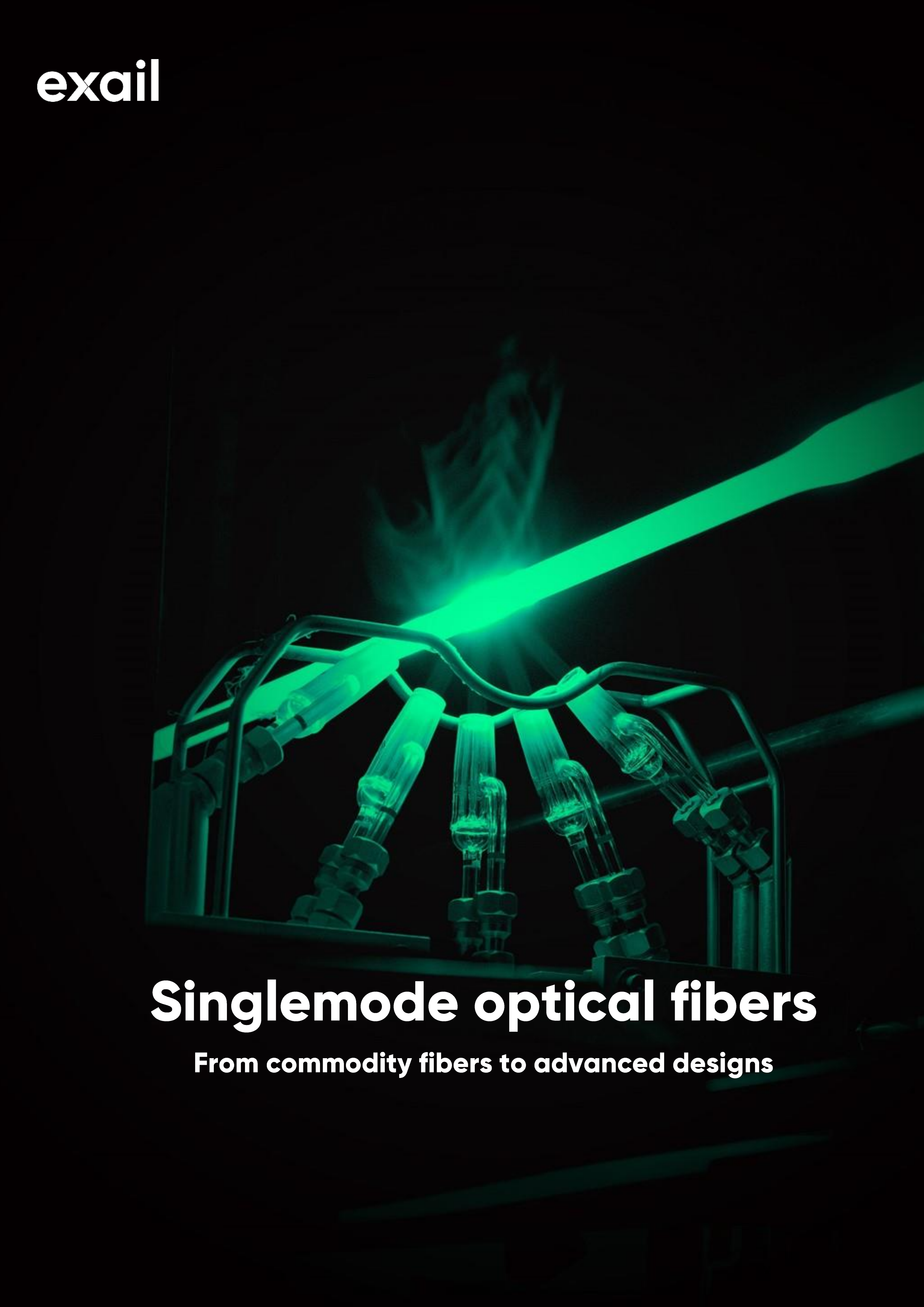
exail



Singlemode optical fibers

From commodity fibers to advanced designs

1 Introduction

Singlemode optical fibers offer low loss, excellent beam quality, and high bandwidth. While singlemode fibers were primarily developed for telecommunication applications around 1550 nm, they are now widely deployed in very diverse fields such as sensing, fiber lasers, interferometry, and Fiber Bragg Grating (FBG) inscription.

A wide range of cost-effective singlemode fibers developed for telecom applications are available in the near infrared wavelengths. However, these fibers were designed for telecom applications and may not always match the specific requirements of other applications, for example in terms of operating temperature range or cladding diameter.

“Exail has 20+ years of expertise in the design and manufacturing of Silica specialty optical fibers and offers a wide range of singlemode fibers”

With over 20 years of expertise in the design and manufacturing of silica specialty optical fibers, Exail offers a wide range of singlemode fibers, from standard commodity fiber to advanced fiber designs. Exail has a wide range of references available in-stock and can also support custom developments, from minor changes to an existing fiber to a completely custom design. Exail’s manufacturing capabilities are as follow:

- Wavelength — 375 to 2000 nm
- Cladding diameter — 40 to 600 µm
- Operating temperature — Cryogenic to +400°C

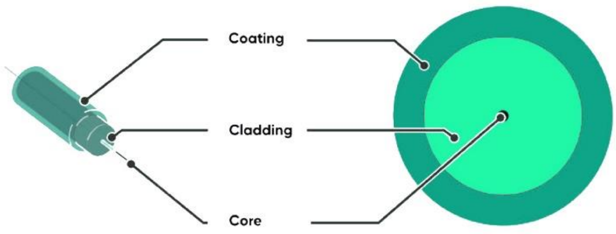


Figure 1 : Schematic representation of a silica singlemode fiber with the core, cladding, and protective coating.

This technical note delves into the main properties of singlemode fibers.

2 Singlemode operation

Singlemode optical fibers have an operating wavelength range limited towards shorter wavelengths by the cutoff wavelength, the wavelength below which the fiber becomes multimode and can support higher-order modes.

For an ideal step-index profile, the singlemode behavior of a fiber can be verified by calculating the normalized frequency number V:

$$V = \frac{2\pi}{\lambda}.r.NA = \frac{2\pi}{\lambda}.r.\sqrt{n_{core}^2 - n_{cladding}^2} \quad (1)$$

With λ the wavelength in vacuum, r the core radius and NA the numerical aperture, defined as $NA = (n_{core}^2 - n_{cladding}^2)^{1/2}$.

"For V numbers below 2.405, the fiber only supports one mode per polarization direction, referred as LP_{01}, and singlemode operation is achieved"

For V numbers ≤ 2.405, the fiber only supports one mode per polarization direction, referred as LP_{01} (LP stands for Linearly Polarized), and singlemode operation is achieved. For V numbers above 2.405, the fiber becomes multimode and the number of modes M can be approximated to be $\sim V^2/2$.

It should be noted that for a given wavelength, the V number is proportional to the product $r.NA$ of the core radius and numerical aperture. Hence, to maintain a constant V number (i.e the same singlemode level), reducing the core radius requires to increase the numerical aperture. Conversely, increasing the core size requires to reduce the numerical aperture to maintain singlemode operation. Consequently, singlemode fibers with a small core diameter must have a high NA, and fibers with a large core diameter must have a low NA to remain singlemode.

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The mode radius w ($@1/e^2$) and Mode Field Diameter (MFD, $@1/e^2$) can be calculated from the core radius r and the normalized frequency V using Marcuse's equation (2) [1]:

$$\frac{w}{r} \sim 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \tag{2}$$

$$MFD\ (@1/e^2) = 2w \tag{3}$$

95% of the optical power of the fundamental LP_{01} mode is contained within the MFD, defined as the diameter where the intensity of the LP_{01} mode drops to $1/e^2 = 13.5\ \%$ of its maximum intensity. It is also well-known that the LP_{01} mode extends into the cladding even under normal operating conditions, resulting in MFD values larger than the core diameter.

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Given that the V number is a function of wavelength, the MFD also varies with wavelength. The leakage of the fundamental LP_{01} mode into the cladding becomes more pronounced towards longer wavelengths, as illustrated in Figure 2 below.

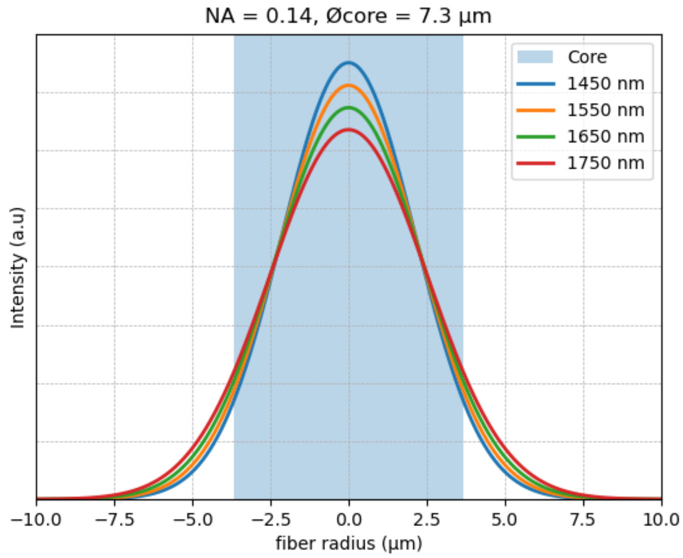

Figure 2 : Representation of the LP_{01} mode within the core (blue region) and cladding at different wavelengths, for a numerical aperture of 0.14 and a core diameter of 7.3 µm.

Using the core characteristics shown in Figure 2 (NA of 0.14, Øcore 7.3 µm), the MFD and percentage of power in the core can be calculated for different wavelengths:

Wavelength	MFD	Fraction of power within the core
1450 nm	8.5 µm	91.4 %
1550 nm	9.0 µm	89.6 %
1650 nm	9.5 µm	87.6 %
1750 nm	10.1 µm	85.4 %

Table 1 : Fraction of power of the LP_{01} mode guided within the core. The remaining power is guided into the cladding, as shown in Figure 2.

“For 1550 nm operation, a 0.14 numerical aperture offers a good compromise between compatibility with other standard fibers and components, and robustness against bending loss”

The increased proportion of the LP_{01} mode being guided into the cladding at longer wavelengths is responsible for the exponential increase of bending loss towards longer wavelengths [2]. The bending loss sensitivity is the main limiting factor of step-index singlemode fibers towards longer wavelengths.

Increasing the numerical aperture provides a tighter confinement of the LP_{01} mode within the core and makes the fiber more robust against both micro and macrobending loss, two important loss mechanisms in singlemode fibers. High Numerical Aperture (HNA) and Ultra-High Numerical Aperture (UHNA) fibers have a NA ≥ 0.20 and offer excellent bending loss resistance, at the expense of a very small core size and MFD required to maintain singlemode operation, as per equation (1).

For 1550 nm operation, a 0.14 numerical aperture offers a good compromise between compatibility with other standard fibers and components, and robustness against bending loss.

3 Loss mechanisms in singlemode fibers

Silica fibers are typically employed from UV wavelengths to ~2.2 µm, which corresponds to the transmission window of silica. The optical attenuation of a singlemode fiber originates from the material properties of the core and cladding, and from the bending losses (micro and macrobending). The optical loss related to the material properties is known to have multiple contributions:

- **Scattering loss**

Also known as Rayleigh scattering, the scattering loss originates from local density or composition inhomogeneities at the microscopic level. Rayleigh scattering has a $1/\lambda^4$ wavelength dependence [3], [4], [5], and is the main loss mechanism of silica fibers in the 400 – 1600 nm wavelength range.

"Rayleigh scattering is the main loss mechanism of silica fibers in the 800 – 1600 nm wavelength range"

- **Infrared absorption**

Infrared absorption originates from multiphonon absorption and becomes the predominant loss mechanism beyond 1700 nm.

- **UV absorption**

Sufficiently energetic UV photons can excite electronic levels within the bandgap of silica, resulting in increased loss. The 10.4 eV bandgap of silica ultimately results in a theoretical transmission edge at 153 nm [3].

- **OH absorption peaks**

The presence of OH hydroxyl groups in the silica matrix results in absorption peaks in the transmission spectrum of optical fibers. While the fundamental absorption band is centered at 2.7 µm, outside the usual operating range of silica fibers, several overtones are present in the near infrared at 940, 1250 and 1385 nm [6].

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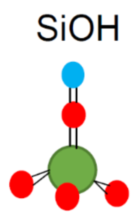

Figure 3 : Structure of the SiOH hydroxyl group, from [7].

Figure 4 below shows the theoretical material loss as a function of wavelength, considering only the Rayleigh scattering and infrared absorption. The measured optical loss of several singlemode fibers with design wavelengths between 375 nm and 1950 nm is superimposed, showing good agreement and transmission levels close to the material limit. The loss increase observed for the IXF-SM-375-010 and IXF-SM-780-014 fibers towards longer wavelengths illustrates how the bending loss limits the operating wavelength range of singlemode fibers.

"The measured optical loss of several singlemode fibers with design wavelengths between 375 nm and 1950 nm shows good agreement and transmission levels close to the fundamental material limit"

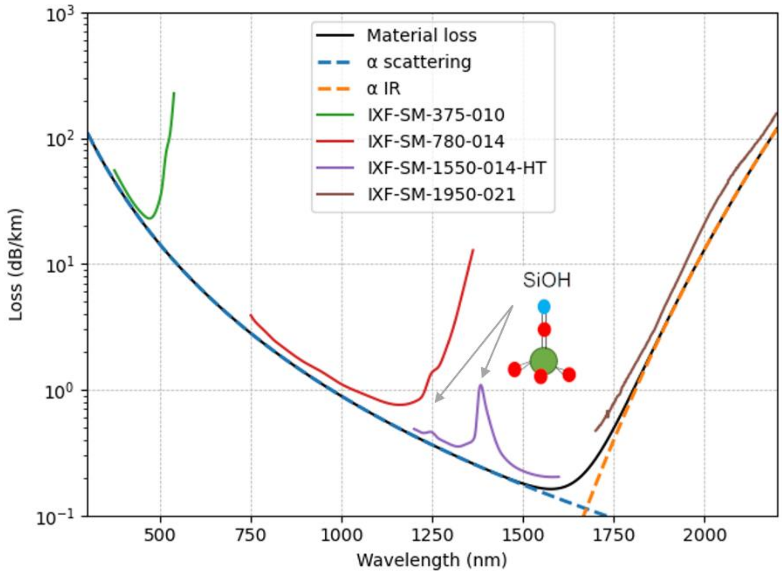

Figure 4 : Theoretical SiO_2 transmission spectrum (black solid line) calculated as the sum of the Rayleigh scattering contribution (dashed blue line) and infrared absorption (dashed orange line). The measured transmission of several singlemode fibers designed for operation at 375, 780, 1550 and 1950 nm is also shown.

4 Refractive index profile and core composition

"The step-index guiding structure can be created using either a Germanium-doped core surrounded by an undoped silica cladding, or by a Pure Silica Core (PSC) surrounded by a Fluorine-doped cladding"

Step-index singlemode fibers can have different core and cladding compositions tailored for specific applications and operating wavelengths. It is well established that the refractive index of silica can be increased by Germanium doping, whereas Fluorine-doped silica has a lower refractive index than silica [8]. The step-index guiding structure can therefore be created using either a Germanium-doped core surrounded by an undoped SiO_2 silica cladding, or by a Pure Silica Core (PSC) surrounded by a Fluorine-doped cladding.

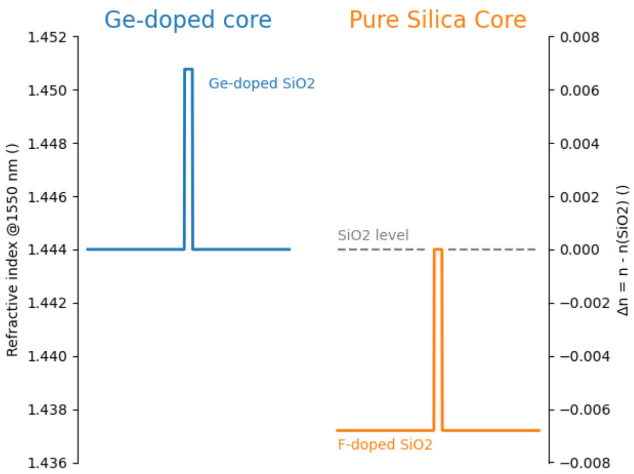

Figure 5 : refractive index profile of an ideal step-index Germanium-doped singlemode fiber (left, in blue) and Pure Silica Core (PSC) fiber (right, in orange) with a 0.14 NA. The refractive index of undoped silica, noted SiO_2 level, is 1.444 at 1550 nm [9].

A numerical aperture of 0.14 corresponds to a refractive index difference $\Delta n = n_{core} - n_{cladding}$ between the core and cladding of 7.10^{-3}, which corresponds to a difference of less than 1% of the refractive index of undoped silica. Despite an identical numerical aperture, the different core composition can have a significant influence on the fiber performance depending on the intended use and environmental conditions.

4.1 Germanium-doped fibers

"The photosensitivity depends on the Germanium concentration and can be further increased with hydrogen loading, a service that Exail can offer, to speed-up the FBG inscription"

Most singlemode fibers have a Germanium-doped core surrounded by an undoped silica cladding. The molar concentration of Germanium can be adjusted to reach the desired core refractive index. High concentrations of Germanium can be incorporated into silica, allowing for the manufacturing of UHNA fibers with a numerical aperture as high as 0.40 ($\Delta n \geq 50.10^{-3}$) that corresponds to a ~30% molar concentration of GeO_2.

Germanium-doped fibers are photosensitive and are commonly used for FBG inscription with UV or femtosecond lasers. The photosensitivity depends on the Germanium concentration and can be further increased with hydrogen loading, a service that Exail can offer, to speed-up the FBG inscription.

Ge-doped fibers are however particularly sensitive to solarization, a darkening of the fiber core that appears with signals below 600 nm. These photons are sufficiently energetic to create color centers, localized defects within the SiO_2 structure that absorb incoming photons. The Solarization-induced loss depends both on the signal wavelength and power density within the core.

4.2 PSC fibers for UV and radiative environments

When the fiber is exposed to high energy particles, for example when operating with UV signal or in a radiative environment, Pure Silica Core (PSC) and Radiation-Hardened fibers are preferred to mitigate the effects of solarization and Radiation Induced Attenuation (RIA) and extend the fiber's lifetime.

Radiation-hardened single-mode fibers have a pure silica core and use dedicated manufacturing processes to mitigate the radiation induced attenuation across the operating wavelength range of the fiber.

5 Coating selection

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. Exail offers a wide range of polymer and metallic coatings able to withstand diverse environments.

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Figure 6 : 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. 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 2 : Typical maximum operating temperature and coating diameter depending on the coating material.

"Exail specialty optical fibers are manufactured with a strong focus on coating quality"

FBG arrays inscribed using femtosecond lasers directly through the acrylate or polyimide coating require a defect-free high-quality coating to achieve 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.

6 Geometrical considerations

The cladding and coating diameters are the two main geometrical specifications. Ø125 µm is the most standard cladding diameter, whereas the nominal coating diameter depends on the coating material (as shown in Table 2) and on the silica cladding diameter.

"Fiber integration, footprint, mechanical reliability under bending, and fiber sensitivity to its external environments are key aspects to consider"

The following aspects should be considered when evaluating the geometry of a fiber:

- **Fiber integration**

Using a standard cladding diameter facilitates the integration of the fiber with commercial off-the-shelf (COTS) components, ferrules and fibers. Most splicers now have built-in programs to splice fibers having different cladding diameters, such as Ø80 µm and Ø125 µm fibers.

- **Footprint**

The cladding and coating diameters have a direct impact on the fiber size, outer diameter, and coiling diameter.

- **Mechanical reliability under bending**

Fibers with a reduced cladding diameter are less stiff and have a lower probability of mechanical failure under bending. When long lengths of fiber need to be tightly coiled, having a reduced cladding diameter such as Ø80 or Ø40 µm can help maintain excellent mechanical reliability despite a tight coiling diameter.

- **Sensitivity to the external environment**

The cladding and coating shield the core from external perturbations. In sensing applications that requires the fiber to be sensitive to external perturbations such as strain, temperature, pressure or acoustic vibrations, having a smaller cladding and/or coating diameter can be advantageous to enhance the sensitivity of the fiber to the measurand (physical property to be measured).
Conversely, increasing the cladding and/or coating diameters is an efficient way to better isolate the core from its surrounding environment, for example to reduce microbending loss.

Exail can manufacture fibers with a cladding diameter between 40 µm and 600 µm, offering great design flexibility. The cladding diameter of the fiber is measured in-line during the fiber draw and after the draw using a calibrated optical microscope, as shown in Figures 7 and 8.

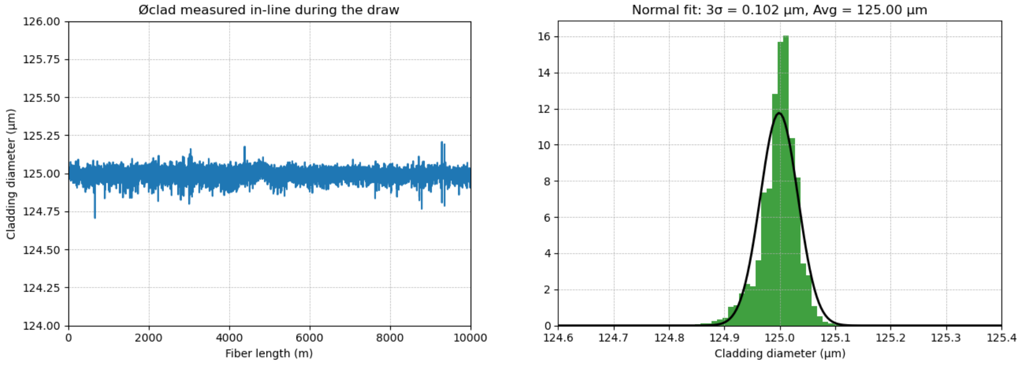

Figure 7 : Example trace showing the cladding diameter measured in-line during the fiber draw (left), and a statistical analysis (right) showing a 3σ value of 0.102 µm.

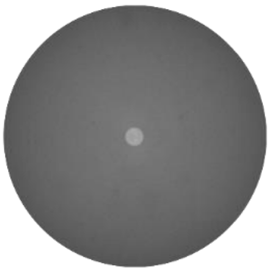

Figure 8 : Cleave of a Ø125 µm cladding Germanium-doped singlemode fiber. The cladding diameter is measured using a calibrated optical microscope.

7 Singlemode fiber selection

"Exail manufactures singlemode fibers designed for operation between 375 nm and 2000 nm with a wide range of numerical apertures, coating materials, and geometries"

Selecting a singlemode fiber for a given application requires to address the desired optical and geometrical caracteristics, as well as the operating environment:

- **Optical** Wavelength, NA, MFD, optical loss
- **Geometrical** Øcladding, Øcoating, bending resistance
- **Environmental** Temperature, radiations, presence of gases, vacuum compatibility

Exail manufactures singlemode fibers designed for operation between 375 nm and 2000 nm with a wide range of numerical aperture, coating materials, and geometries. These fibers are grouped into the following product families depending on the target applications:

- IXF-SM Singlemode fibers, Ge-doped
- IXF-RAD-SM Radiation-hardened singlemode fibers (Pure Silica Core)
- IXF-PHO Photosensitive fibers, with standard NA, HNA or UHNA

The product code contains the main optical and geometrical characteristics to facilitate fiber selection. For example, the product codes of the IXF-SM family are constructed as follow:

IXF-SM-1550-125-014-PI

Design wavelength	Ø cladding	Numerical aperture	Coating
1550 nm	125 µm	014: 0.14	Blank: Acrylate
1300 nm	80 µm	019: 0.19	HT: High-temperature acrylate
980 nm		028: 0.28	PI: Polyimide
780 nm			AL: Aluminum
375 nm			

Other references not listed on Exail's website may be available, please contact your sales representative for any enquiry. Exail also welcomes custom developments, from minor adjustments to an existing fiber up to more complex developments.

8 Conclusion

With over 20 years of expertise in the field of specialty optical fibers, Exail offers a wide range of singlemode fibers for operation from UV wavelengths to 2000 nm.
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 also provides solutions for harsh environments, with advanced coating materials such as Polyimide. Aluminum-coated fibers developed within the 3F2E project can complement polymer coated fibers for the most demanding applications.

9 References

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