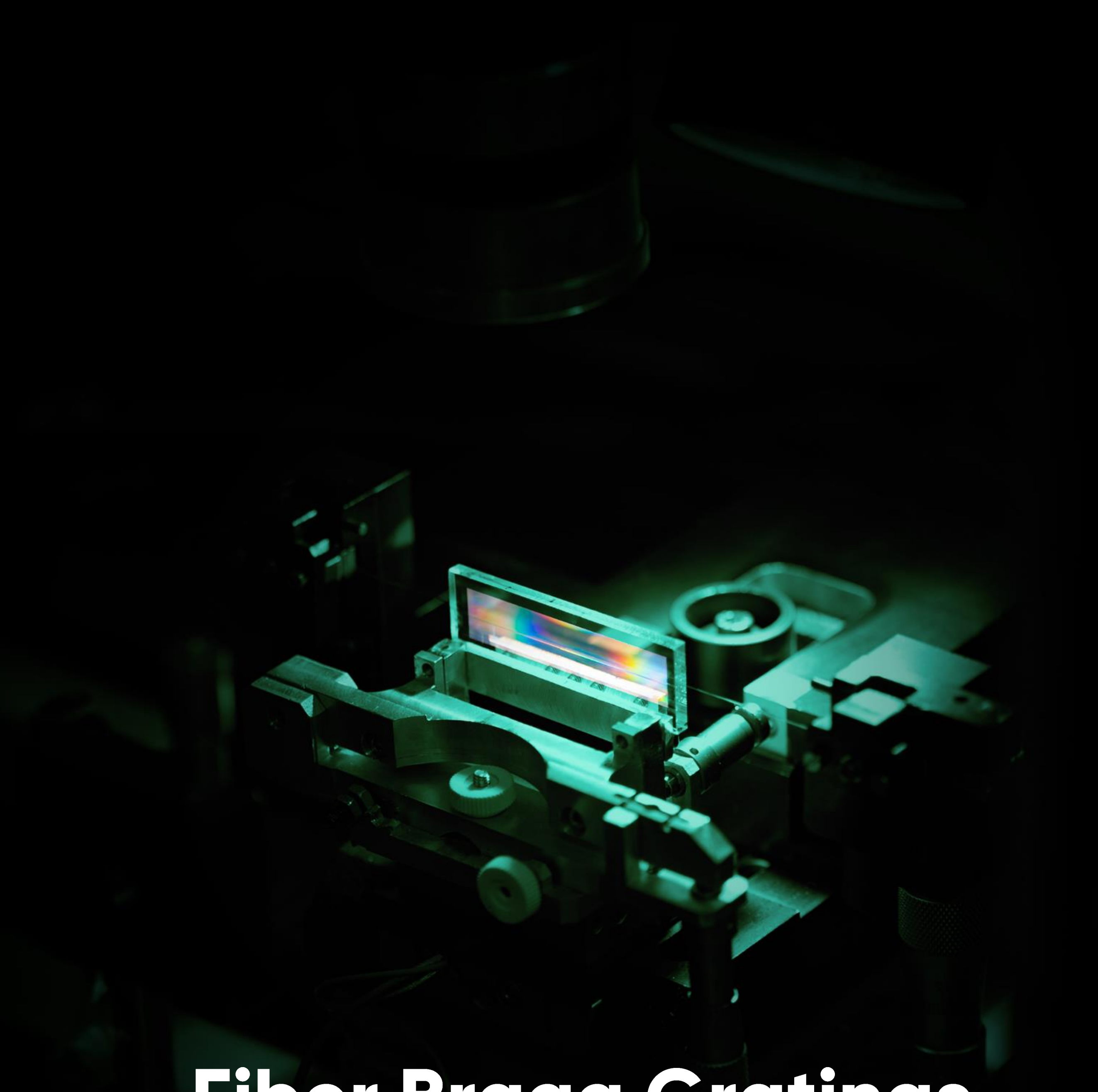

# Fiber Bragg Gratings

## manufacturing methods and tailored optical fibers

1 INTRODUCTION .......... 2
2 FBG CHARACTERISTICS .......... 3
3 FBG MANUFACTURING METHODS .......... 4
4 EXAIL'S FBG MANUFACTURING CAPABILITIES .......... 7
5 SPECIALTY FIBERS FOR FBG MANUFACTURING .......... 8
5.1 SINGLEMODE AND PM FIBERS .......... 9
5.2 CLADDING MODE SHIFTED FIBERS .......... 11
5.3 CLADDING MODE FREE FIBERS .......... 11
6 CONCLUSION .......... 12
7 REFERENCES .......... 13

# 1 Introduction

Fiber Bragg Gratings (FBG) are fiber-based optical components found in a variety of applications such as Wavelength Division Multiplexing (WDM), Gain Flattening Filters (GFF), dispersion compensation or emulation [1], fiber lasers, frequency stabilization of DFB or Fabry-Perot lasers, and acoustic, strain or temperature sensing.

With over 20 years of expertise in FBG and specialty optical fibers manufacturing, Exail offers a wide range of FBGs, and silica fibers tailored for FBG inscription. This technical note reviews the main methods and characteristics of manufacturing FBG. It includes a general overview of Exail's FBG manufacturing capabilities and portfolio.

"Exail has 20+ years of expertise in the design and manufacturing of FBGs and silica fibers tailored for FBG inscription"

A FBG is a filtering element offering low insertion loss and wide design flexibility. In its simplest form, a FBG consists of a permanent periodic modulation of the core refractive index of a singlemode fiber. The refractive index profile along the fiber gives rise to the typical transmission and reflection spectrum shown in Figure 1.

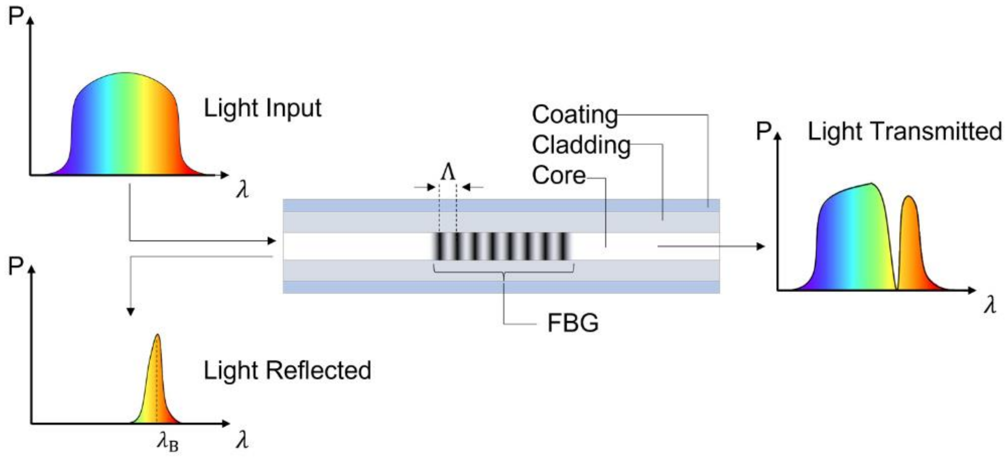


*Figure 1 : schematic representation of a FBG with the transmitted and reflected spectrum, from [2].*

The reflected wavelength, also known as the Bragg Wavelength, can be calculated from the grating period $\Lambda$ and the effective refractive index $n_{eff}$ the of the $LP_{01}$ fundamental mode as:

$$\lambda_B = 2.n_{eff}.\Lambda$$

It is worth noting that the grating period is typically of the same order as the operating wavelength, making the manufacturing process very sensitive to environmental conditions.

## 2 FBG characteristics

Despite its seemingly simple working principle, numerous types of FBGs have been developed, leading to virtually limitless FBG design possibilities and characteristics. The various types of FBG are distinguished by the profile of the refractive index modulation inscribed into the fiber core. Figure 2 below shows a representation of the refractive index profile of several FBG types: uniform, apodized, chirped and pi-shifted FBGs.

“The various types of FBG are distinguished by the profile of the refractive index modulation inscribed into the fiber core”

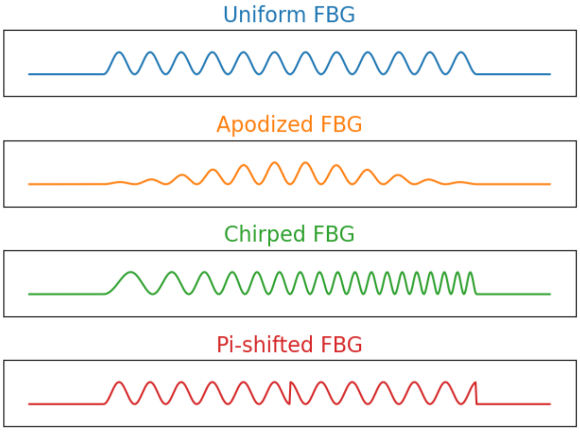


*Figure 2 : schematic representation of the core refractive index profile along the fiber for different types of FBG: uniform, apodized, chirped and pi-shifted.*

Each type of FBG exhibits distinct optical characteristics, including center wavelength, bandwidth, reflectivity, and side lobe suppression ratio (SLSR), as illustrated in Figure 5. In practical applications, uniform FBGs tend to have a relatively low SLSR, whereas apodized profiles offer superior SLSR performance along with high reflectivity and narrow bandwidth. Chirped (or apodized chirped) FBGs are designed to achieve a broader bandwidth than uniform (or apodized) FBGs, due to the varying grating period along their length.
Additional parameters such as the FBG length, the amplitude of the refractive index modulation, the envelope shape on apodized gratings (e.g sine, Gauss, or SuperGauss) all play critical roles in the final performance of the FBG.

Other types of FBG exist, such as tilted FBG or long period gratings (LPG), these FBG being somewhat less common.

# 3 FBG manufacturing methods

Two main manufacturing methods exist, femtosecond and UV laser inscription.

- **Femtosecond laser inscription**

A femtosecond (fs) laser is focused on the core of the optical fiber using an objective lens, with each pulse locally modifying the refractive index of the core. By translating the fiber in front of the objective lens, a desired refractive index profile modulation can be created along the fiber length. The grating period $\Lambda$ is then directly determined by the pulse repetition rate and the translation speed.

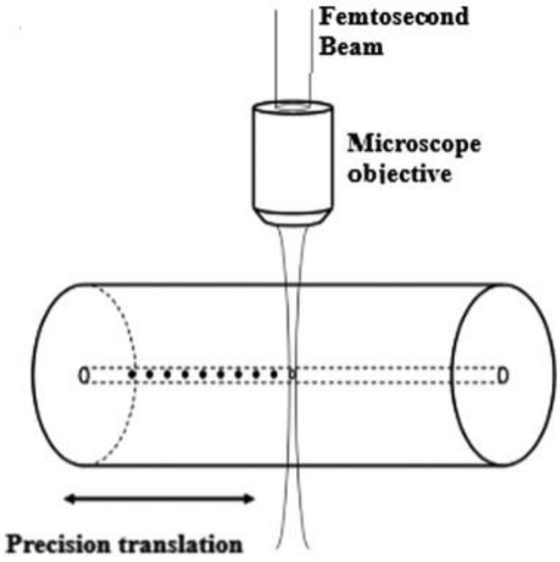


*Figure 3 : representation of fs-FBG inscription, from [3]. Also known as the point-by-point (PbP) method, fs-FBG can be inscribed directly through the acrylate or polyimide coating.*

"Fs-laser FBG can be directly inscribed through the coating, which improves manufacturing efficiency by eliminating the need to strip the polymer coating before inscription"

Femtosecond lasers used for fs-FBGs inscription can operate within a wavelength range where polymer coatings like acrylate and polyimide are relatively transparent. As a result, fs-laser FBG can be directly inscribed through the coating, which improves manufacturing efficiency by eliminating the need to strip the polymer coating before inscription. Direct inscription through the coating also enables the fully automated production of FBG arrays consisting of hundreds or even thousands of FBGs.

Fs-FBGs do not require photosensitive fiber and can be inscribed on both germanium-doped and Pure Silica Core (PSC) fibers. This capability paves the way for the development of radiation-hardened FBG designs, particularly those inscribed on Rad-Hard PSC fibers [4].

- **UV laser inscription**

The second manufacturing method employs a UV laser source and an interference pattern, which is created using a phase mask or various configurations such as Lloyd's mirrors or a Talbot interferometer.

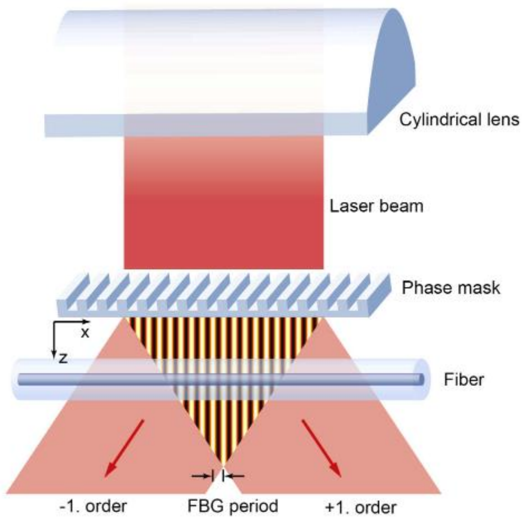


*Figure 4 : Representation of a phase mask used to create the interference pattern needed for UV inscription of FBG, from [5].*

Pulsed Excimer lasers (e.g 193, 248 nm) or diode pumped solid-state lasers paired with nonlinear optics (e.g 193, 213 or 266 nm) are typically used, but continuous wave UV lasers, such as frequency-doubled Argon ion lasers (244 nm), are also common. When using photosensitive fibers, the periodic interference pattern permanently modifies the core's refractive index through the photorefractive effect.

Unlike fs-FBG, UV inscription requires the use of photosensitive fibers. Germanium-doped fibers are known for their photosensitivity, which is directly related to the concentration of Germanium. The photosensitivity of Ge-doped fibers can be increased by up to two orders of magnitude through hydrogen loading before FBG inscription [6]. This enhancement either accelerates the UV inscription process or allows for greater refractive index modulation within a given time frame.

"UV inscription requires the use of photosensitive fibers. Germanium-doped fibers are known for their photosensitivity, which can be further enhanced with hydrogen loading before FBG inscription"

Boron-doped fibers or Boron co-doped Germanium fibers are known to be highly photosensitive, although Boron doping significantly increases the optical attenuation of the fiber and can reduce the long-term stability of the grating.

The fiber photosensitivity directly impacts the FBG inscription time which must be kept short enough to achieve sufficient manufacturing yield and avoid any environmental drift during the inscription.

Polymer coatings such as acrylate or polyimide are opaque to UV wavelengths. As a result, the fiber must be locally stripped of its coating to perform the FBG inscription on bare (uncoated) fiber. This short length of fiber is usually recoated after the FBG inscription is completed.

# 4 Exail's FBG manufacturing capabilities

Exail uses UV inscription and phase masks to manufacture FBG. FBG can be written in Germanium-doped optical fibers either manufactured by Exail or provided by the customers. $H_2$ loading is possible depending on the intrinsic photosensitivity of the fiber.

"Exail uses UV inscription and phase masks to manufacture a wide range of FBG, including apodized, chirped, gain flattening, and pi-shifted FBG"

Exail can manufacture a wide range of FBG, including apodized, chirped, gain flattening, and pi-shifted FBG.

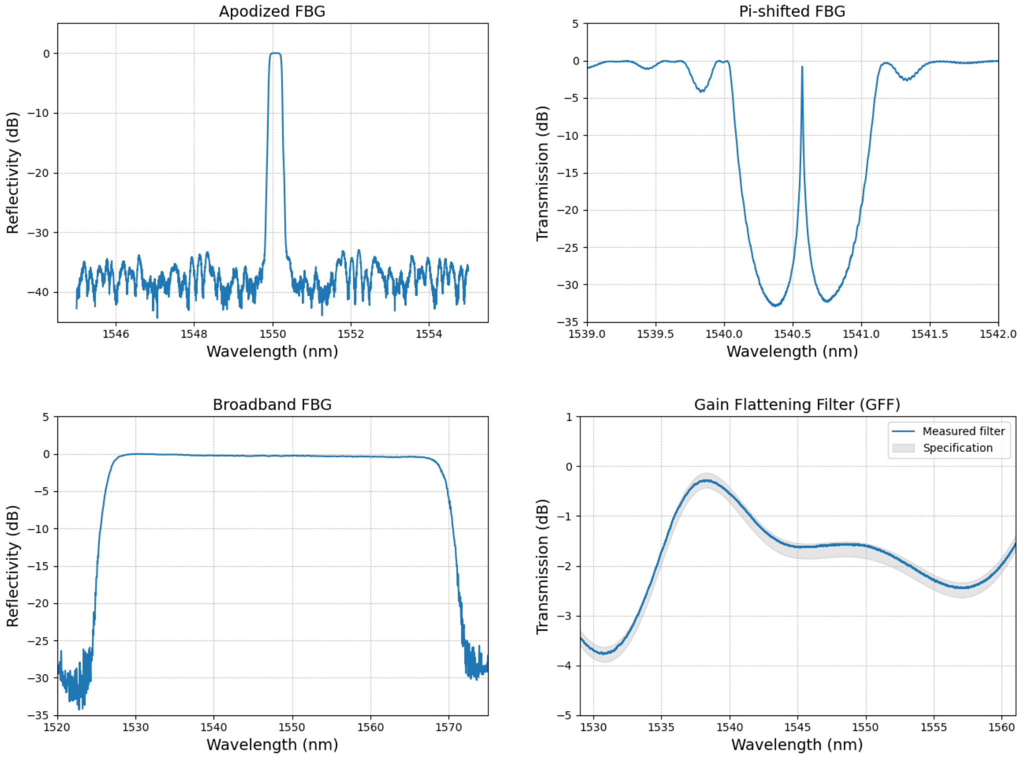


*Figure 5 : typical transmission profile of Exail's apodized (top-left), pi-shifted (top-right), chirped (bottom-left) and GFF (bottom-right) FBGs.*

"FBG can be delivered as bare fiber or enclosed in wavelength-adjustable or athermal packages for easy handling and integration"

FBGs with a Bragg wavelength ranging from 350 nm to 2.2 µm can be manufactured with low insertion loss, typically below 0.2 dB. The bandwidth and reflectivity can be tailored to the customer's requirements, ranging from 1 GHz (pi-shifted) to several tens of nanometers (chirped), and reflectivities from 4 to over 99.9 %. FBG can be delivered as bare fiber or enclosed in wavelength-adjustable or athermal packages for easy handling and integration.


*Figure 6 : Exail's FBG can be delivered as bare fiber or packaged in standard or athermal packages.*

Exail can also provide FBG on multicore fibers, for applications such as gain flattening in multicore amplifiers [7], [8]. Additionally, we offer Rad-Hard FBGs inscribed on radiation-hardened fibers to mitigate the Radiation Induced Bragg Wavelength Shift (RI-BWS) in radiative environments [4].

"Volume production and custom developments are possible for various types of FBG"

Volume production and custom developments are possible for various types of FBG, contact your sales representative for any enquiry.

# 5 Specialty fibers for FBG manufacturing

FBGs are fiber-based optical components, and as such, the properties of the optical fiber play an important role in both the manufacturing steps and the final characteristics of the FBG.

"Specialty optical fibers can provide the additional design flexibility required to meet demanding requirements, compared to standard telecom optical fibers"

FBGs can be manufactured using standard telecom fibers like SMF28 widely available at several common telecom wavelengths. When specific fiber parameters need to be adjusted, specialty optical fibers can provide the additional design flexibility required. This can include considerations such as design wavelength, photosensitivity, fiber geometry or coating material.
Exail designs and manufactures silica optical fibers for operation across a wavelength range from 350 nm to 2.2 µm, with various core and cladding composition, core and cladding size, and coating materials. This section aims to provide an overview of the different fiber types relevant for FBG manufacturing.

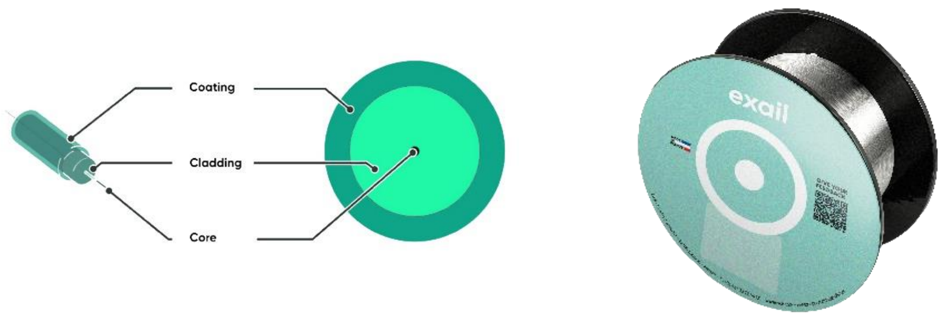


*Figure 7 : Exail designs and manufactures silica specialty optical fibers, including different types of PM and non-PM singlemode fibers for FBG manufacturing.*

## 5.1 Singlemode and PM fibers

"Exail offers a range of PM and non-PM Germanium-doped singlemode fibers for femtosecond and UV FBG inscription"

Exail offers a range of singlemode fibers, both PM and non-PM, which can be used for FBG manufacturing. These Germanium-doped fibers are compatible with femtosecond and UV inscription.

The IXF-SM and IXF-PM are families of singlemode fibers designed for operation from 350 to 2200 nm, available with various cladding diameters and numerical apertures. For UV inscription, acrylate-coated fibers are preferred thanks to the possibility to easily strip and recoat the fiber.

"Exail's specialty fibers are manufactured with a strong focus on coating quality, achieved through rigorous cleanliness standards, optimized manufacturing processes, and dedicated monitoring instruments"

In addition, Exail also offers fibers with a Pure Silica Core (PSC) or with a polyimide coating. These PSC or polyimide-coated fibers are particularly suitable for femtosecond FBG inscription. When FBGs or FBG arrays are inscribed using femtosecond lasers directly through acrylate or polyimide coatings, a defect-free, high-quality coating is essential to achieve high inscription yield and consistently meet FBG specifications. Exail's specialty fibers are manufactured with a strong focus on coating quality, achieved through rigorous cleanliness standards, optimized manufacturing processes, and dedicated monitoring instruments.

FBG inscribed on regular step-index singlemode fibers can be affected by cladding modes, which affect the transmission and reflection profile of certain types of FBG, as discussed in the next section.

### 5.1.1 CLADDING MODES

Cladding modes are optical modes that can exist in the cladding of an optical fiber [9]. When light travels along the core of an optical fiber, cladding modes are not excited, and the signal remains well confined within the $LP_{01}$ fundamental mode. However, refractive index variations, such as those created along an FBG, can excite counter-propagating cladding modes. A detailed discussion of cladding modes is beyond the scope of this technical note but is also available in [9]. Cladding modes are particularly noticeable in high-reflectivity FBGs (>50 %) where they can cause transmission losses larger than 3 dB over more than 20 nm [10].

"Cladding modes are usually not visible in the reflection spectrum and solely affect the transmission profile, manifesting as ripples or multiple peaks on the short-wavelength side of the Bragg wavelength"

Due to the presence of a high-index polymer coating, counter-propagating cladding modes are not guided effectively and are quickly absorbed by the coating. In the case of narrow FBG, cladding modes are usually not visible in the reflection spectrum and solely affect the transmission profile, manifesting as ripples or multiple peaks on the short-wavelength side of the Bragg wavelength, as shown in Figure 8. For broadband chirped FBGs with widths of several nanometers, cladding modes impact both the transmission and reflection profiles. This can be qualitatively understood because the cladding modes excited by the longer wavelengths of the chirped FBG now fall within its bandwidth if the light is injected at the long-period side of the grating. As a result, some of the energy within the bandpass is coupled into cladding modes rather than being reflected into the core, which results in a reflection profile with up to several dB of non-uniformity, as shown in Figure 10.

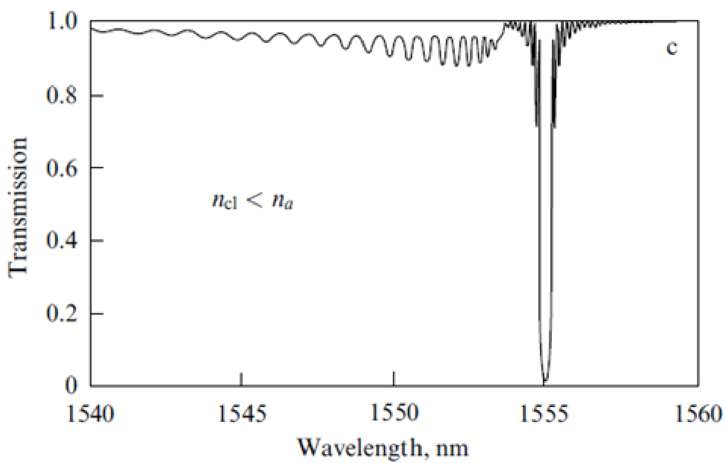


*Figure 8 : Simulated transmission profile of a singlemode fiber with a FBG centered at 1555 nm, the cladding modes appear as a ripple clearly visible between 1540 and 1554 nm, from [9].*

Cladding modes are undesired in the context of FBG manufacturing, and their effect can be mitigated or even largely suppressed using Cladding Mode Shifted (CMS) or Cladding Mode Free (CMF) fibers which are discussed in the next sections.

## 5.2 Cladding Mode Shifted fibers

Cladding Mode Shifted (CMS) are Ge-doped step-index singlemode fibers with high or ultra-high numerical apertures. The small Mode Field Diameter (MFD) resulting from the high Germanium concentration of the core physically shifts the cladding modes further away from the Bragg wavelength, towards shorter wavelengths. Exail manufactures CMS fibers with numerical apertures of 0.21 and 0.37, resulting in cladding modes shifts of 4 and 9 nm respectively. Although cladding modes are not suppressed, their displacement from the Bragg wavelength helps to mitigate interference when working with FBGs at closely spaced wavelengths.

Due to their high or ultra-high Germanium concentration, CMS fibers are also more photosensitive than Ge-doped singlemode fibers having a numerical aperture of 0.12 – 0.14.

## 5.3 Cladding Mode Free fibers

Cladding Mode Free (CMF) are step-index singlemode fibers which virtually eliminate all cladding modes. CMF fibers were first reported in [10] and use a special cladding composition, making the inner region of the cladding as photosensitive as the core itself through Germanium and Fluorine co-doping. The co-doping in the inner cladding with Germanium and Fluorine, two dopants which affects the refractive index of silica in opposite ways, make it possible to match the refractive index of silica while having the photosensitivity of Ge-doped silica.

The refractive index profile and doping profile are schematically represented in Figure 9.

"Cladding Mode Free (CMF) are step-index singlemode fibers which virtually eliminate all cladding modes and enable the manufacturing of FBG with near-ideal transmission and reflection profiles"

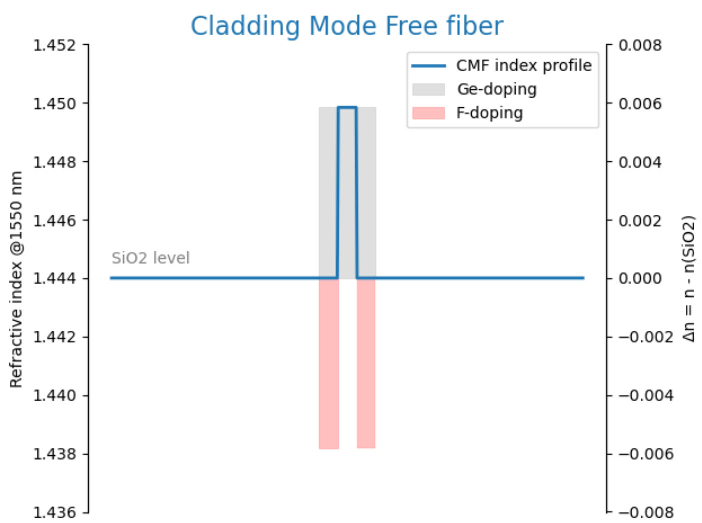


*Figure 9 : schematic refractive index profile of a CMF step-index singlemode fiber, showing Ge-doping in the core and inner cladding, and F-doping in the inner cladding.*

As a result, the FBG extends into the cladding which eliminates any coupling of the fundamental mode to cladding modes. CMF fibers enable the manufacturing of FBG with near-ideal symmetrical transmission and reflection profiles and cladding modes as low as 0.2 dB. Exail's CMF fibers are available for 1 µm and 1550 nm operation, other wavelengths may be available upon request.

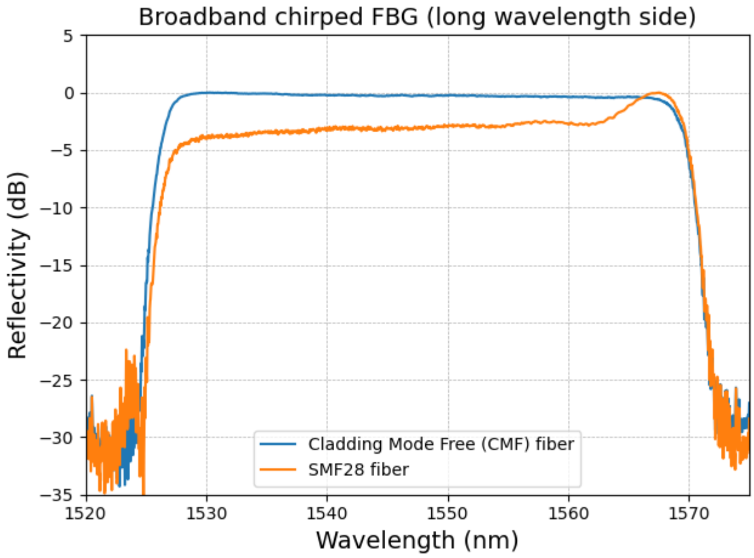


*Figure 10 : schematic representation of the reflection spectrum of a broadband chirped FBG from the long wavelength side, inscribed on a SMF28 fiber (orange) or on a cladding mode free fiber (blue).*

# 6 Conclusion

With over 20 years of expertise in the field of FBG manufacturing, Exail offers a wide range of low-loss FBGs for applications such as fiber cavity reflectors or gain flattening filters across the visible and NIR wavelengths.

Exail also designs and manufactures specialty optical fibers for FBG production across the UV to NIR spectrum. We provide PM and non-PM step-index singlemode fibers with various coating options, including standard acrylate, high-temperature acrylate or polyimide coatings, to suit different operating environments.
In addition, CMS and CMF are singlemode fibers tailored specifically for high performance FBG manufacturing and allow to mitigate or eliminate the effects of cladding modes.

- IXF-SM Singlemode fibers, Ge-doped
- IXF-PMF PM singlemode fibers, Ge-doped
- IXF-PHO Cladding Mode Shifted and Cladding Mode Free singlemode fibers

Exail is equipped with the necessary manufacturing tools and processes to address both large-scale productions and custom developments of both FBG and specialty optical fiber.

Exail also offers solutions for harsh environments, featuring advanced coating materials such as polyimide and aluminum. Aluminum-coated fibers developed within the 3F2E project can complement polymer coated fibers for the most demanding applications, including high-temperature FBG

# 7 References

[1] K. Fröjdh, “Manufacturing of Very Long Fiber Bragg for Dispersion Compensation Applications,” in *Advanced Photonics & Renewable Energy*, Karlsruhe: OSA, 2010, p. BMA1. doi: 10.1364/BGPP.2010.BMA1.

[2] F. Falcetelli, A. Martini, R. Di Sante, and M. Troncossi, “Strain Modal Testing with Fiber Bragg Gratings for Automotive Applications,” *Sensors*, vol. 22, no. 3, p. 946, Jan. 2022, doi: 10.3390/s22030946.

[3] J. K. Sahota, N. Gupta, and D. Dhawan, “Fiber Bragg grating sensors for monitoring of physical parameters: a comprehensive review,” *Opt. Eng.*, vol. 59, no. 06, p. 1, Jun. 2020, doi: 10.1117/1.OE.59.6.060901.

[4] A. Morana *et al.*, “Radiation Effects on Fiber Bragg Gratings: Vulnerability and Hardening Studies,” *Sensors*, vol. 22, no. 21, p. 8175, Oct. 2022, doi: 10.3390/s22218175.

[5] T. A. Goebel *et al.*, “Femtosecond inscription of semi-aperiodic multi-notch fiber Bragg gratings using a phase mask,” *Opt. Express*, vol. 28, no. 24, p. 35682, Nov. 2020, doi: 10.1364/OE.405498.

[6] I. Riant, “Fiber Bragg gratings for optical telecommunications,” *Comptes Rendus Physique*, vol. 4, no. 1, pp. 41–49, Jan. 2003, doi: 10.1016/S1631-0705(03)00013-6.

[7] Y. Wakayama, N. Yoshikane, and T. Tsuritani, “FIFO-less Core-pumped Multicore Fibre Amplifier with Fibre Bragg Grating based Gain Flattening Filter,” p. 4.

[8] Y. Wakayama, N. Yoshikane, and T. Tsuritani, “FIFO-less Core-pump Combiner for Multicore Fiber Amplifier,” in *Optical Fiber Communication Conference (OFC) 2021*, Washington, DC: Optica Publishing Group, 2021, p. M3D.3. doi: 10.1364/OFC.2021.M3D.3.

[9] O. V. Ivanov, S. A. Nikitov, and Y. V. Gulyaev, “Cladding modes of optical fibers: Properties and applications,” *PHYS-USP*, vol. 49, no. 2, p. 167, 2006, doi: 10.1070/PU2006v049n02ABEH005784.

[10] E. Delevaque *et al.*, “OPTICAL FIBER DESIGN FOR STRONG GRATINGS PHOTOIMPRINTING WITH RADIATION MODE SUPPRESSION,” in *Optical Fiber Communications Conference*, San Diego, California: OSA, 1995, p. PD5. doi: 10.1364/OFC.1995.PD5.