

Optical Signal Attenuation in an FBG Sensor Network for Aerospace Systems Monitoring

Original

Optical Signal Attenuation in an FBG Sensor Network for Aerospace Systems Monitoring / Aimasso, A., Bertone, M., Maggiore, P., Dalla Vedova, M.D.L.. - In: JOURNAL OF PHYSICS. CONFERENCE SERIES. - ISSN 1742-6588. - 3179:(2026). (16th International Conference on Vibration Measurements by Laser and Noncontact Techniques, AIVELA 2025 Ancona (ITA) 24/06/2025 - 26/06/2025) [10.1088/1742-6596/3179/1/012005].

Availability:

This version is available at: 11583/3016828 since: 2026-10-20T10:10:09Z

Publisher:

Institute of Physics

Published

DOI:10.1088/1742-6596/3179/1/012005

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

PAPER • OPEN ACCESS

Optical Signal Attenuation in an FBG Sensor Network for Aerospace Systems Monitoring

To cite this article: Alessandro Aimasso *et al* 2026 *J. Phys.: Conf. Ser.* **3179** 012005

View the [article online](#) for updates and enhancements.

You may also like

- [Design and development of innovative FBG-based fiber optic sensors for aerospace applications](#)
M D L Dalla Vedova, P C Berri, P Maggiore *et al.*
- [Analysis of the fixing process of FBG optical sensors for thermomechanical monitoring of aerospace applications](#)
Alessandro Aimasso, Matteo D.L. Dalla Vedova, Alfredo Esposito *et al.*
- [Rapid prototyping of FBG-based optical sensors for vibration analysis of mechatronic systems](#)
Matteo D L Dalla Vedova, Gaetano Quattrocchi, Alessandro Aimasso *et al.*

Enabling Electrochemistry Inside and Outside the Lab



Discover our diverse range of Potentiostats engineered
to support your research wherever it takes you

- Intuitive software for Windows and Android
- Proven in over 4000 scientific publications
- Single-channel and multi-channel
- Benchtop, portable and wearable

Discover More



Optical Signal Attenuation in an FBG Sensor Network for Aerospace Systems Monitoring

Alessandro Aimasso^{1*} , Matteo Bertone¹ , Paolo Maggiore¹  and Matteo D.L. Dalla Vedova¹ 

¹ Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy

*E-mail: alessandro.aimasso@polito.it

Abstract. In the field of aerospace systems monitoring, Fiber Bragg Grating (FBG) sensors have emerged as a promising technology due to their high sensitivity, multiplexing capability and immunity to electromagnetic interference. However, the design and implementation of an FBG-based optical sensor network for systems monitoring present significant challenges, particularly related to signal attenuation. Optical signal losses, resulting from multiple factors such as fiber curvature, splices, connectors, feedthroughs, and the number of FBGs in the network, can critically affect the accuracy and reliability of the acquired data. This paper presents an initial investigation into the optical signal attenuation mechanisms in FBG sensor networks for aerospace applications. The ultimate objective of this study is to support the preliminary design phase of such networks by developing a predictive tool capable of estimating the total signal attenuation as a function of the geometric configuration of the network. To this end, firstly a comprehensive literature review was conducted, focusing on the main sources of attenuation, including bending losses due to fiber curvature, junction and insertion losses, and the cumulative effects of multiple FBGs in a single network. Building on this bibliographic analysis, the authors propose the development of a computational algorithm designed to estimate the overall optical signal attenuation in a given FBG sensor network. The algorithm incorporates input parameters such as the number and type of splices, the presence of feedthroughs, the number and location of FBGs, connector characteristics, and fiber curvature radii along the path. The aim is to provide designers with a practical and scalable tool to evaluate signal integrity at the early stages of sensor network design, helping to ensure optimal placement and minimal signal degradation throughout the system.

1. Introduction

The use of sensors is essential for the design, testing, and industrialization of engineering systems capable of ensuring high performance, long-term reliability, and the ability to operate in harsh environments. These requirements are particularly stringent in the aerospace sector, whose inherent complexity demands the development of solutions that maximize each of the aforementioned aspects. Optical fiber sensing technology, thanks to its unique physical properties, effectively meets these requirements. In particular, Fiber Bragg Grating (FBG) sensors offer the possibility of combining high sensitivity and minimal footprint, ensuring immunity to



electromagnetic interference, the absence of electrical currents within the sensing network, the use of chemically inert materials, and the capability to multiplex different sensors along the same communication line, even for the measurement of different parameters. However, the large-scale industrial application of these sensors, especially in the aerospace field, is still limited by several factors. Firstly, optical/electronic interfaces have been developed, industrialized, and certified only for specific engineering sectors and/or particular applications. Secondly, there is no universally defined methodology for the assembly of optical lines for the development of sensor networks, nor are there certified industrial strategies for their integration into engineering systems and installations. In particular, due to the mechanism of optical signal generation and transmission, the construction of an FBG sensor line can introduce losses that may compromise the quality of the transmitted data.

The purpose of this work is therefore to identify the types of optical signal losses that inevitably occur during the assembly process of a typical FBG-sensorized fiber. The paper is organized as follows:

- *Section 2* briefly describes how the fiber works, the main sources of optical loss occurring during the assembly of an FBG monitoring line and their quantification.
- *Section 3* outlines the experimental campaign conducted to measure the contribution of each identified loss mechanism, with results compared to key references and models.
- *Section 4* presents a simple graphical software tool developed to estimate, a priori, the optical losses in a measurement line based on its known physical and geometrical characteristics.

2. Optical fiber signal transimission and losses in sensors arrays

An optical fiber consists of a multilayer glass filament capable of guiding a light signal along its core. Widely used for decades in telecommunications for data transmission, optical fibers can also be employed for sensing applications. Among the different technologies available on the market, Fiber Bragg Grating (FBG) optical sensors represent the best compromise in terms of performance-to-cost ratio. In simple terms, an FBG sensor can be described as a short section (approximately 1 cm) of optical fiber that, through a specific fabrication process, reflects a precise wavelength of the electromagnetic spectrum propagating through the fiber. This reflected wavelength is defined as:

$$\lambda_B = 2n_{eff} \Lambda \quad (1)$$

It can thus be immediately inferred that the optical output is correlated to the grating period itself, which effectively becomes the measurable output of the sensor. Consequently, during the design of an optical measurement line, it is essential to ensure that both the incoming and outgoing optical signals reach the instrumentation with sufficient power. A typical measurement setup consists of three main components:

- an interrogator;
- a personal computer (PC);
- at least one optical fiber line containing one or more sensors.

The interrogator is the component that generates the electromagnetic spectrum transmitted through the optical fibers. Simultaneously, it detects the wavelengths reflected by the gratings and sends the processed data to the PC, where they are stored. The measured physical signal therefore travels twice—first from the interrogator to the sensor, and then back from the sensor to the interrogator.

A generic measurement line, however, is characterized by several elements that prevent the transmission from being ideal:

- *Curvatures*, required to guide the optical fiber from the interrogator to the measurement point;
- *Splices*, necessary to multiplex different sensors or to connect fiber sections and connectors;
- *Connectors* providing the mechanical interface between the fiber and the measurement instrumentation.

Each of these elements—together with the physical characteristics of the materials employed—introduces optical signal losses along the fiber path, resulting in a reduction of signal intensity. Since the measurement system must detect specific wavelengths to determine particular physical parameters, it is crucial to design the overall geometry of the optical line such that the total attenuation ensures that all FBG reflections remain above a relative intensity threshold of 20%, which is the minimum level required by the instrumentation to distinguish the response peak from background noise.

The primary sources of attenuation are as follows:

- *Material absorption loss*, due to the intrinsic absorption of light by the fiber material, as well as impurity ion absorption loss, caused by the presence of impurities such as metallic ions and OH^- ions within the fiber. Additionally, scattering loss arises from the diffusion of the optical signal within the fiber medium [1-3]. The combined effect of these losses defines the intrinsic attenuation of the fiber, typically expressed in dB/km, which can be determined based on the specific fiber type by consulting the manufacturer's technical specifications [4-6].
- *Microbending loss*, resulting from the presence of microscopic bends in the fiber that induce local variations in the propagation conditions [7-8].
- *Macrobending loss*, caused by macroscopic bends that alter the refractive index distribution, thereby affecting the transmission efficiency of the optical signal [9-10].
- *Connector-to-connector loss*, introduced by the presence of optical connectors used to establish temporary or detachable connections between multiple fiber segments [11].
- *Fusion splicing loss*, associated with the permanent joining of multiple fiber sections through fusion splicing techniques [12].
- *FBG insertion loss*, referring to the influence that each Fiber Bragg Grating (FBG) sensor exerts on the overall signal transmission along the optical line [13].

For each of these attenuation sources, reference values or mathematical models were identified in the literature and used as the starting point for the development and subsequent validation of the computational code.

2.1 Optical losses estimation model

In order to develop a tool capable of estimating the overall optical power loss during the design phase of a specific measurement line, it is necessary to define an appropriate computational model. The total optical loss measured by the instrumentation results from the combination of the physical properties of the materials used and the geometric characteristics of the designed optical path. In its most general form, the model allows for the identification of the overall optical power loss as:

$$L_{tot} = 2(L_f + L_b + L_c + L_s) \quad (2)$$

Where:

- L_f represents the optical loss induced by the material properties of the fiber, including absorption and microbending effects;
- L_b accounts for the losses due to macrobending, i.e., the geometric curvatures imposed on the fiber;
- L_c refers to losses induced by optical connections (splices, feedthroughs, connectors);
- L_s represents the losses introduced by the FBG sensors located upstream of the considered measurement point

In the present work, each of these contributions are quantified according to relations reported in scientific literature, experimentally verified, and implemented in a computational software interface designed to support the engineering and design process of optical measurement lines.

The contribution L_f depends on the physical characteristics of the specific optical filament employed. It is typically expressed as attenuation in [dB/km], a value generally provided by the fiber manufacturer. This total attenuation includes two main components:

- *Intrinsic attenuation* of the fiber material;
- Losses due to *microbending* effects.

The term L_c depends on the optical connections present along the fiber line and is calculated as the sum of:

- Losses due to *connector insertion*;
- Losses from *fusion splicing* between fiber segments;
- Losses due to *feedthroughs* along the optical path.

Each of these losses is quantified based on the technical data provided by the component manufacturer, while the splicing losses are measured directly by the fusion splicer at the end of each joining process.

The L_{fs} contribution identifies the loss introduced by each FBG sensor located upstream of the considered point along the optical network.

The L_b term accounts for the attenuation resulting from macrobending, that is the power loss induced by the geometric path imposed on the fiber. Estimating the variation of optical properties as a function of the imposed bending radius is a complex task, due to the simultaneous interaction between the spectral characteristics of the incident light and the mechanical and optical properties of the fiber layers (core and cladding). Using the simplified Marcuse model [14], the attenuation coefficient can be expressed as:

$$2\alpha = \frac{\pi^{1/2} k^2 \exp\left(-\frac{2\gamma^3 R_{eff}}{3\beta^2}\right)}{2R_{eff}^{1/2} \gamma^{3/2} V^2 K_{m-1}(\gamma a) K_{m-1}(\gamma a)} \quad (3)$$

Where:

- a is the core radius;
- $V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$ is the normalized frequency of the optical fiber, with n_1 e n_2 being the refractive indices of the core and cladding, respectively, and λ the incident wavelength;
- $\beta = k_0 n_{eff}$ con $k_0 = 2\pi/\lambda$ and n_{eff} the effective refractive index;

- $\gamma = \sqrt{\beta^2 - k_0^2 n_2^2}$ describes the exponential decay of the field in the cladding region;
- $k = \sqrt{k_0^2 n_1^2 - \beta^2}$ represents the radial oscillation rate within the core;
- K_ν denotes the modified Hankel function of order;
- $R_{eff} = 1,28R$ is the Schermer and Cole relation [15], which accounts for elasto-optic effects and refractive index deformation induced by real curvature R .

Considering R_{eff} as the only geometry-dependent parameter of the specific optical system (since all other parameters are fixed by the fiber material and light source, both predefined), the model was simplified for implementation in the overall loss estimation as:

$$\alpha = \frac{A}{\sqrt{R_{eff}}} e^{-BR_{eff}} \quad (4)$$

In which parameters A and B are calculated from relation (3).

Finally, from the same relation it is possible also to estimate the bending loss induced by a specific number N of complete circular windings:

$$L_N = \eta N \quad (5)$$

In which η is the loss of a single winding calculated with the equation (3).

3. Test campaigns

The laboratory test campaign was structured into three main phases. At first, the effect of fiber curvature on signal transmission was analyzed. Subsequently, point losses at optical connections were investigated. Finally, the influence of individual sensors on signal intensity during transmission was evaluated.

3.1 Losses induced by bending radius and number of windings

The scope of this part is an experimental campaign in which, by modifying the fiber's bending radius and measuring the corresponding signal loss, it is possible to estimate the trend of the attenuation coefficient α [dB/mm]. This allows for verifying whether the theoretical model implemented in the computational code is consistent with the experimental data. To reproduce the desired bending conditions as accurately as possible, a series of small cylindrical molds were designed using CAD and subsequently fabricated via 3D printing in resin. Each cylinder had a height of 1 cm and a different radius, around which the optical fiber could be wrapped. After winding the fiber around each cylinder, adhesive tape was applied to keep it in position and to prevent excessive tension or oscillations in the output signal. For this study, a range of curvature radii between 4 mm and 15 mm was selected to encompass the most relevant cases. The results confirmed that the mathematical model implemented in the computational code is in good agreement with laboratory data (Figure 1). The only notable discrepancy was observed for very small bending radii (approximately below 6 mm), for which the model provides less accurate estimates due to oscillatory phenomena that prevent precise numerical prediction. The effects of such tight bends should ideally be treated using more sophisticated mathematical approaches, such as perturbation theory models. Nevertheless, in practical applications, such extreme bending conditions are typically avoided because the output signal intensity becomes excessively low. Furthermore, the experimental results had been well confirmed also in the case of multiple winding optical fiber path, both in terms of bending radii and number of windings.

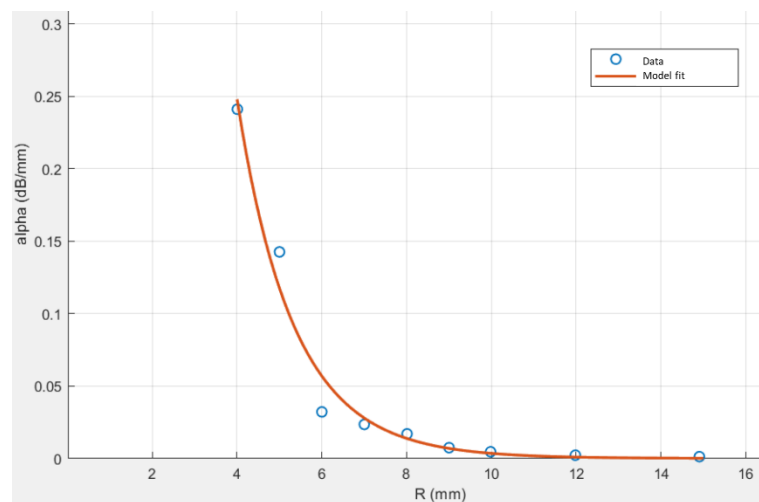


Figure 1. Comparison between experimental data and the simplified model fit for different bending radii.

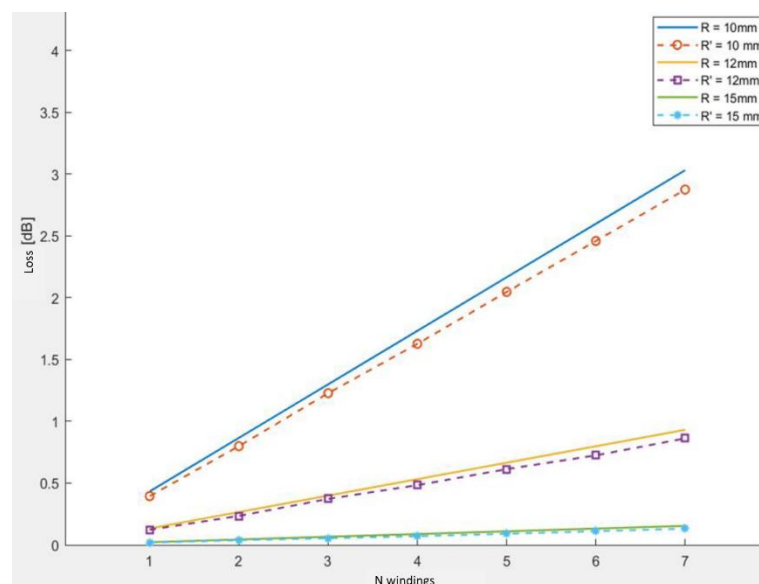


Figure 2. Comparison between experimental data and the simplified mathematical model, for different bending radii and number of windings.

3.2 Losses induced by connections

A second experimental phase focused on analyzing losses due to optical connections. The underlying hypothesis was that increasing the number of optical interconnections between fibers leads to a gradual reduction in output optical power, as losses accumulate at each connection point. To investigate this effect, several optical connections were created between fiber segments using FC/APC-type connectors. The first step involved measuring the loss associated with the connection between the interrogator and the optical fiber. Subsequently, two additional FC/APC connections were added sequentially along the fiber, and data were acquired after ensuring proper alignment using optical feedthroughs. From the collected data, the *average loss per connector pair* was estimated to be approximately 0.24 dB, in close agreement with the datasheet value of 0.25 dB typically associated with this type of optical connection. More specifically, individual measurements showed slight variations among the three pairs of connectors (0.245 dB, 0.234 dB, and 0.249 dB, respectively), highlighting that—besides alignment—the cleanliness

of the connector surfaces significantly influences signal transmission, often in a non-negligible manner.

3.3 FBG Sensor-Induced Losses

The final experimental phase examined the losses associated with the presence of the sensors themselves along the optical fiber. In addition to the instrumented fiber used for previous measurements, three additional fibers of the same type were employed, each equipped with FBG sensors tuned to different Bragg wavelengths. The goal of this test was to observe the reflected signal peak from the second sensor and to verify whether its power was reduced due to the presence of the first upstream sensor. To this end, the additional fibers were connected in series to the first one using FC/APC connectors, for which the loss values had already been characterized in the previous phase. By analyzing the relative signal intensity reflected by the second sensor, the estimated losses were 0.15 dB, 0.17 dB, and 0.18 dB, respectively. These results confirm that the losses remained consistently below 0.25 dB, in agreement with the manufacturer's specifications reported in [7], where the standard FBG insertion loss is indicated as ≤ 0.25 dB.

4. Software interface development

For the development of the software interface, a dedicated code was written in *Python*, using the Tkinter graphical user interface (GUI) toolkit. The interface was designed to initially collect the main input parameters, such as the *intrinsic attenuation* of the optical fiber, the *microbending losses*, the *connector losses* associated with the selected optical interconnections, and the *attenuation induced by FBG sensors* distributed along the fiber. After this preliminary setup, an additional section of the interface was implemented to allow the user to specify which elements are actually present along the optical path and therefore contribute to signal attenuation. These elements must be selected in order, starting from the one closest to the signal source and proceeding downstream along the optical line. Regarding the *connectors*, it is assumed that all are of the same type (FC/APC in the present case). Consequently, the only required input is the number of connections, since the default loss value per connection is already predefined among the input parameters.

A similar assumption applies to the FBG sensors, for which the insertion loss is considered equal to the upper limit observed experimentally and reported in the literature. Therefore, the user is only required to input each sensor's Bragg wavelength and distance from the signal source (in km). In contrast, for fiber splices, no predefined loss value is assumed, as the attenuation depends strongly on the alignment quality of the joined fiber sections. Hence, the user must manually enter the measured loss value corresponding to each performed splice.

A dedicated section of the interface was also created for evaluating bending losses, providing the user with the ability to select the type of curvature to which the fiber is subjected and to input the corresponding geometric parameters. The implemented model is based on the simplified theory of Dietrich Marcuse, which allows the estimation of the attenuation coefficient along a bent fiber segment as a function of the bending radius. This coefficient is then multiplied by the length of the affected fiber segment to determine the total optical power loss.

The input parameters required from the user depend on the selected configuration:

- The *number of windings* and *bending radius*, for complete circular windings;
- The *bending radius* and *winding angle*, if the fiber is not bent through a full 360°;
- The *number of windings* and the major (a) and minor (b) semi-axes, in the case of complete *elliptical winding*.

The elliptical configuration was treated using the same general model as the other two cases but with a different computational approach. Since the bending radius is not constant along an elliptical path, the attenuation coefficient varies point by point. Therefore, a numerical integration function was implemented within the code to estimate the total loss along the ellipse. This approach inevitably introduces approximation errors particularly when the semi-axes a and b are both very small. For this reason, whenever the user selects this configuration type, a *warning message* is displayed, informing that the estimated loss may have reduced accuracy.

Finally, the *Calculate and Plot* option was developed to aggregate all user-provided data, call the respective computational functions, and sum all individual contributions, displaying all relevant results in the output window. Additionally, the plotting function generates a graphical representation of the signal spectrum and the reflected intensity peaks from the sensors, producing a visualization similar to that obtained from an optical interrogator (Figure 3).

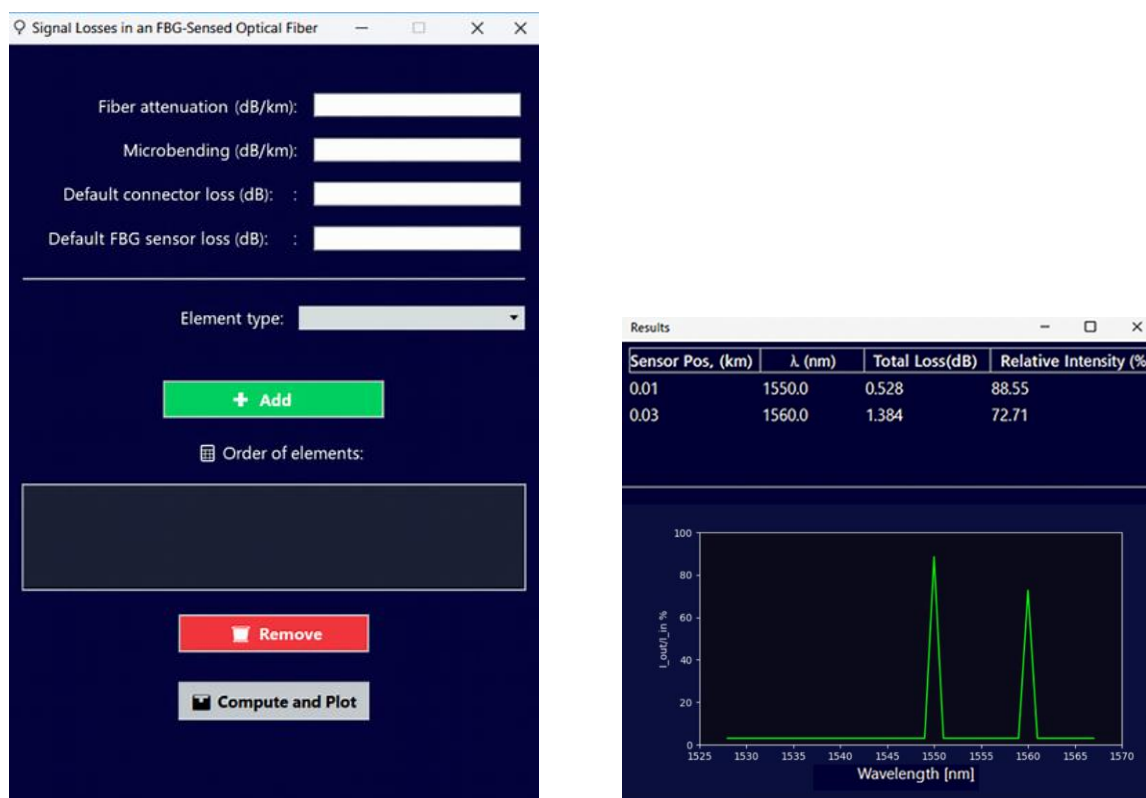


Figure 3. Graphical interface for the total optical line loss estimation. On the left, the starting page, in which the user can set the physical fixed parameter and add the specific elements of the considered geometry; on the right the final output of the model, with the total loss quantification and final FBG intensity signal simulation.

5. Conclusions

The experimental campaign yielded significant results regarding the main sources of optical signal attenuation. With reference to bending losses, the experimental data made it possible to define a validity range for the theoretical model — both for constant-radius and variable-radius curvatures. This identified range is consistent with the theoretical framework developed by physicist D. Marcuse, whose mathematical model served as the foundation for the implemented computational code. Regarding localized losses at optical connections and FBG sensors, the

experimental findings also showed a strong agreement with the theoretical reference values adopted within the calculation model.

Therefore, it can be concluded that the developed software interface can be considered a reliable tool for providing a first-order estimation of the expected optical signal losses along a given sensorized optical fiber geometry

Acknowledgments

Authors sincerely thanks dott. Andrea Orlando and dott. Mattia Rapone for their great support offered during the test campaigns and the literature review process.

References

- [1] H. A. Macleod. Analysis of OH absorption bands in synthetic silica. *Journal of Non-Crystalline Solids*, 203:15–25, 1996.
- [2] G. P. Agrawal. *Nonlinear Fiber Optics*. Academic Press, 5th edition, 2002.
- [3] M. K. Barnoski and J. M. Jensen. Rayleigh backscattering in single-mode optical fibers. *Applied Optics*, 15(5):1220–1223, 1976.
- [4] P. D. D. Marquis, R. E. D. Hobson, and M. E. Becker. Impurity-induced absorption in silica fibers. *Journal of Lightwave Technology*, 5(5):769–774, 1987.
- [5] Optical Fiber Loss and Attenuation, Fosco Connect, <https://www.fiberoptics4sale.com/blogs/archive-posts/95048006-optical-fiber-loss-and-attenuation> Example reference
- [6] Pure Silica Core SM Fibers, Fibercore, Humanetics, <https://fibercore.humaneticsgroup.com/products/single-mode-sm-fiber/pure-silica-core-sm-fiber/sm1500sc780>
- [7] Qiu, D. Zheng, K. Zhu, B. Fang, L. Cheng, Optical Fiber Sensor Experimental Re-search Based on the Theory of Bending Loss Applied to Monitoring Differential Settlement at the Earth-Rock Junction, Hindawi Publishing Corporation, Journal of Sensors Volume 2015, Article ID 346807
- [8] T. Erdogan. Microbend loss in single-mode fibers. *IEEE Photonics Technology Letters*, 5(5):498–500, 1993.
- [9] Dietrich Marcuse. Curvature loss formula for optical fibres. *Journal of the Optical Society of America*, 66:216–220, 03 1976.
- [10] Ross T. Schermer, Member, IEEE, and James H. Cole, Improved Bend Loss Formula Verified for Optical Fiber by Simulation and Experiment, IEEE Journal of Quantum Electronics, Vol. 43, No. 10, October 2007
- [11] FC/APC Fiber Connectors: Single Mode, Thorlabs https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=6246
- [12] Himanshu Gaurav, What is Optical Fibre Splice Loss, STL Tech, 04 May 2022 <https://stl.tech/blog/what-is-optical-fibre-splice-loss/>
- [13] G. Keisers, Fiber Optic Communications, Malla Reddy Engineering College (MRCE), p.416, Table 10.5
- [14] Dietrich Marcuse. Curvature loss formula for optical fibers. *Journal of the Optical Society of America*, 66:216–220, 03 1976.
- [15] Ross T. Schermer and James H. Cole. Improved bend loss formula verified for optical fiber by simulation and experiment. IEEE Journal of Quantum Electronics