Sensitivity analysis of FBG sensors for detection of fast temperature changes

Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Sensitivity analysis of FBG sensors for detection of fast temperature changes

Journal of Physics: Conference Series **2590** (2023) 012006 doi:10.1088/1742-6596/2590/1/012006

Sensitivity analysis of FBG sensors for detection of fast temperature changes

Alessandro Aimasso Matteo Davide Lorenzo Dalla Vedova Paolo Maggiore

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

alessandro.aimasso@polito.it

Abstract. In the last few decades, the use of optical fiber is becoming more widespread for communication technologies and sensor applications. In this sense, considering the physical characteristics of the fiber, there are many possibilities for its use in various engineering sectors, not least in the aerospace one. Indeed, using optical fibers to replace traditional electronic devices can provide significant advantages, such as using an extremely lightweight and minimally invasive technology. FBG (Fiber Bragg Grating) sensors are ones of the most widely used instruments for this purpose, and they allow the detection of different physical parameters, including temperature. The aim of the present work is to analyze the performances of FBGs, in particular by evaluating their ability to read short-term thermal transients and comparing it with that of a conventional thermal probe (PT100). More specifically, two optical fibers were used: the first with the FBG sensor area covered by the external coating and the second without this outer layer. All instrumentation was placed in a climatic chamber and subjected to different thermal cycles. Furthermore, the fiber sections with FBGs were not placed directly in contact with the plate on which they were installed. This made it possible to put optical sensors indications that were as independent as possible from the materials on which they were mounted. Tests have shown that optical sensors have an extremely high sensitivity and a much shorter reaction time than the PT100 probe. Data collected by this work allow strategic use of FBG for thermal monitoring using a minimally invasive and extremely accurate technology.

1. Introduction

Optical fiber is a consolidate technology with the primary property of transmitting a light signal inside itself [1]. Because of this property, optical fiber has revolutionised the communication industry as well as a wide range of novel technical applications [2]-[8]. However, throughout the last several decades, one of the most explored elements of scientific study has been the application of optical technology for sensor creation [9]-[11]. Sensors are becoming increasingly crucial in more complicated engineering projects for measuring system performance over the course of the system's lifespan. There is an increasing demand for equipment that can operate in adverse, if not entirely harsh, environmental conditions [12], [13].

Optical fiber-based sensors, particularly Fibre Bragg Grating (FBG) sensors, can satisfy these requirements due to the unique benefits afforded by fibre optics [14]-[16].

The capacity to operate successfully in unfavourable settings is a fundamental demand in the aerospace industry [12], [17]. Temperature, mechanical deformation, pressure, vibration, and other physical characteristics crucial to system monitoring may be measured with great sensitivity using FBG sensors. The proper integration of optical sensors in the safety-critical components of the primary aircraft and/or spaceship onboard systems is a particularly motivating aim in this respect.

In this paper, the sensitivity of FBG to thermal transients will be the main topic. In more detail, the authors will concentrate on the sensor sensitivity to rapid thermal transient; by comparing different packaging techniques and the results to a reference PT100 sensor.

The data collected will enable the development of an innovative activity of prognostics, diagnostics and system performance evaluation.

2. Optical fiber and FBG sensors

A standard optical fibre has a cylindrical construction with many concentric layers from the inside to the outside known as core, cladding, and coating. The outer coating, like the other outside layers, serves merely to counterbalance the extreme fragility of the glass fibre that makes up the inner layers. The core and cladding, on the other hand, are the two layers that allow the fibre to physically work properly. In reality, if light is fed into the core with the proper direction, when it reaches the interface between the core and the cladding, it undergoes a complete reflection phenomenon, propagating inside the fibre.

The FBG optical fibre trait has a maximum length of 1 cm. A laser photo incision is employed inside the core to impose a periodic modification of the refractive index. The resulting structure functions as a selective frequency mirror. Except for a certain frequency that is reflected in the opposite direction, the whole electromagnetic spectrum that goes through the fibre also passes through the grating. Because the reflected frequency is related to the sensor's shape, it is also proportional to the physical characteristics that might affect it.

For example, it is a highly light and less intrusive material, resulting in substantial weight savings in tiny component instrumentation. Furthermore, the tiny size of the fiber's cable section, along with the ability to install many sensors on the same communication line, helps decrease disturbances, especially during thermal testing [23]. Another critical component is the optical fiber's resistance to electromagnetic interference. When combined with its wide working temperature range, it ensures good performance even in harsh conditions. Finally, the fibre is perfect for monitoring potentially explosive settings such as tanks since it is chemically inert and electrically passive.

3. Experimental set-up and test campaign

The key part of the devised experimental setup is the optical data collection system. The interrogator is the most significant component: in this study, a Smart Scan interrogator from the Smart Fibres company is employed. This component creates a laser beam, which is delivered into the optical fibres to which it is attached through its communication channels. As observed in the last chapter, when the laser beam strikes the FBG gratings, they reflect a certain frequency. The reflected frequencies are returned to the interrogator and quantified as wavelengths [24]. The data is subsequently transmitted to the computer through a LAN cable, where it is displayed on a monitor and stored in a text file.

The fibres connecting to the interrogator were put in a climate chamber in the part holding the FBG sensor. A 5Pascal KK50 climatic chamber is employed in particular. For temperature regulation, the aforementioned climatic chamber is outfitted with a PT100 sensor. The role of humidity was overlooked in this experimental effort.

Inside the climatic chamber, *3 FBGs* are placed as reported in fig. 1. Two of them are in fibers that are fixed on two metal supports, but with the sensor zone completely free from any materials. This is done to focus solely on the response provided by the sensors, without detecting the effects of other materials on sensors. The only difference between these two FBGs is the presence, in the first one, of the external coating on the sensor, and not in the second one. The third sensor, instead, is placed inside a polymer cylinder that has suitable fissures for air passage, in order to evaluate the sensor performance when inserted in a prototype packaging. All sensors are positioned in the climatic chamber as shown in the fig. 2. The reference measurement is made with the PT100 integrated into the chamber’s temperature control.

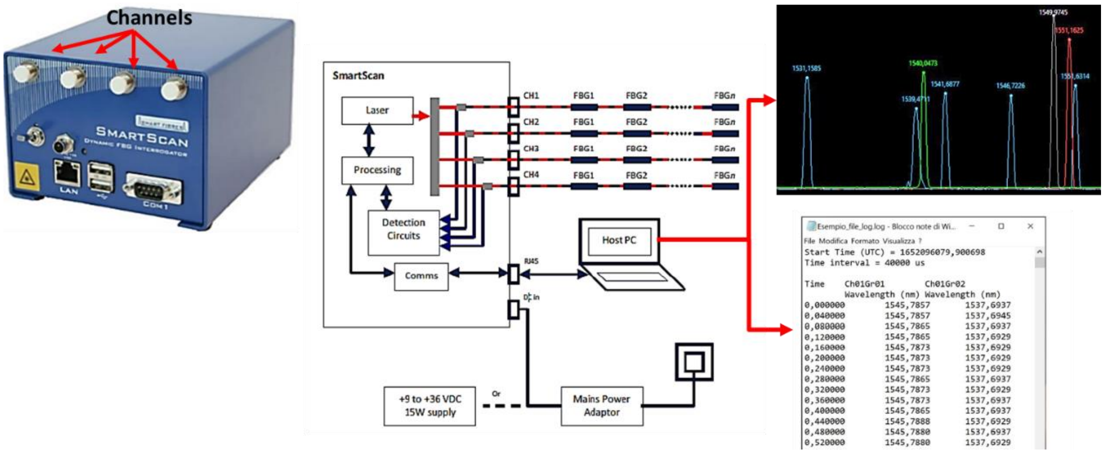

Figure 1. Scheme of optical data acquisition system

Figure 2 Sensors placed in the climatic chamber (on the left) and details about their set-up (on the right)

The following thermal cycle is repeatedly applied to the experimental setup:

1. The climatic chamber is closed and brought to a temperature of 120°C for enough time to reach thermal equilibrium.
2. The door of the climatic chamber is opened, applying a sudden thermal transient to the measurement environment.
3. The climatic chamber is closed again but remaining turned off. The heat accumulated on the metal plates reheats the sensors, causing a new thermal transient.

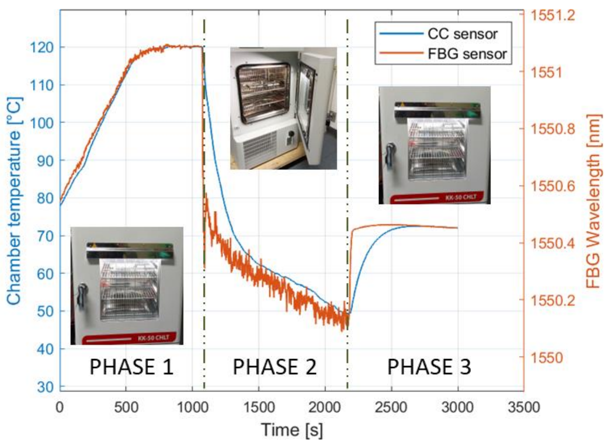

Figure 3. Scheme of thermal cycle applied in the test campaign

The thermal cycle applied to the experimental setup generates different environmental conditions to which the system is exposed. In the first heating phase, the climatic chamber is activated. It starts to heat the internal environment. No disturbances are present, and only oscillatory phenomena induced by the airflow generated by the activity of the chamber can be detected. In the second phase, the chamber is turned off, and at the same time, the door is opened. In this way, the experimental setup undergoes a drastic and sudden decreasing thermal transient governed by the hot air flow exiting the chamber. During this phase, a first comparison of the response time of the different sensors used is carried out. In the third phase, the chamber is still off, but the door is closed again. The presence of still hot metal walls heats the sensors again. A second comparison of the response time is thus possible between the sensors, this time in an increasing transient.

4. Results and discussions

At a general level, for all the sensors both in the rising and falling phase, the presence of a second-order dynamic can be observed, which involves the superposition of two different dynamics:

- A first, extremely fast, dynamic, which indicates the rapid thermal transient imposed on the sensor.
- A second, much slower, dynamic which describes the evolution of the system towards a state of equilibrium.

Mathematically, by interpolating the experimental data in MATLAB®, all the recorded evolutions were modeled as follows:

$$y(t) = Ae^{Bt} + Ce^{Dt}$$

Therefore, by analysing the evolution recorded in transients of the different sensors, it is possible to verify and compare the effect of the reaction time for each one. In particular, the value is calculated as

$$\tau = -\frac{1}{B}$$

This result does not precisely represent the time constant of the sensor since it also includes the time constant of the physical cooling/heating phenomenon imposed by the opening/closing of the chamber. However, the geometry of the experimental setup imposes the same environmental conditions on all sensors. Therefore, the differences recorded between them are attributable to the different reaction times specific to each sensor.

The overall thermal cycle has been repeated 20 times. In Table 1 the mean values are reported for each sensor. The main trends are also reported in the following figures.

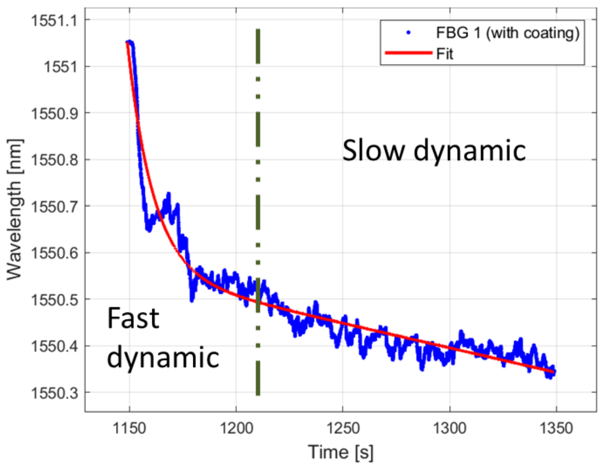

Figure 4. Example of a transitory phase

Table 1. Mean values of time constants

Phase	Sensor	Time constant [s]
Cooling	FBG 1	0,085
	FBG 2	0,071
	FBG casing	0,717
	PT100	0,848
Heating	FBG 1	0,262
	FBG 2	0,218
	FBG casing	0,513
	PT100	0,719

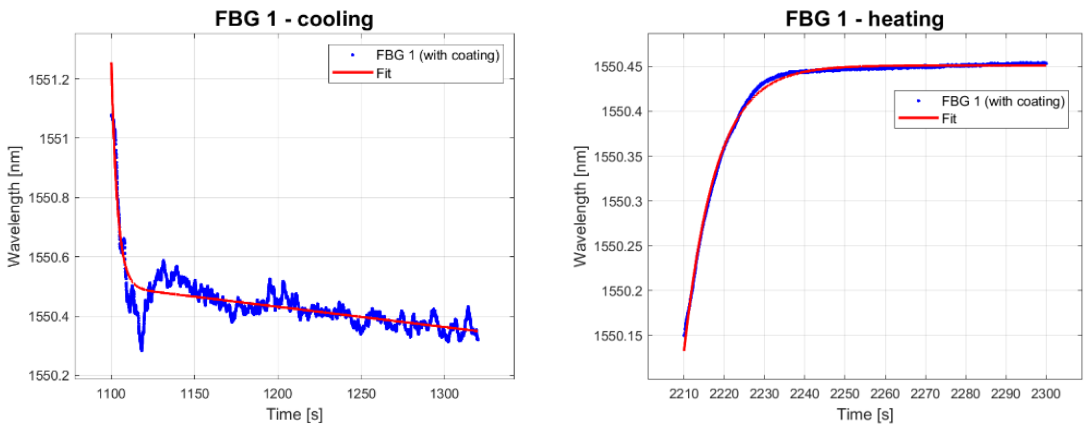

Figure 5. Transients of FBG 1 (with coating) at decreasing (left) and increasing (right) temperature

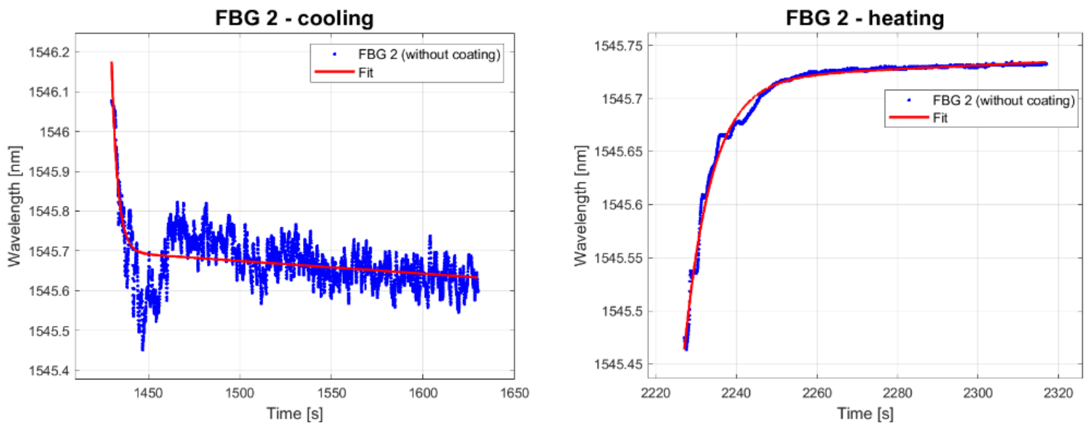

Figure 6. Transients of FBG 2 (without coating) at decreasing (left) and increasing (right) temperature

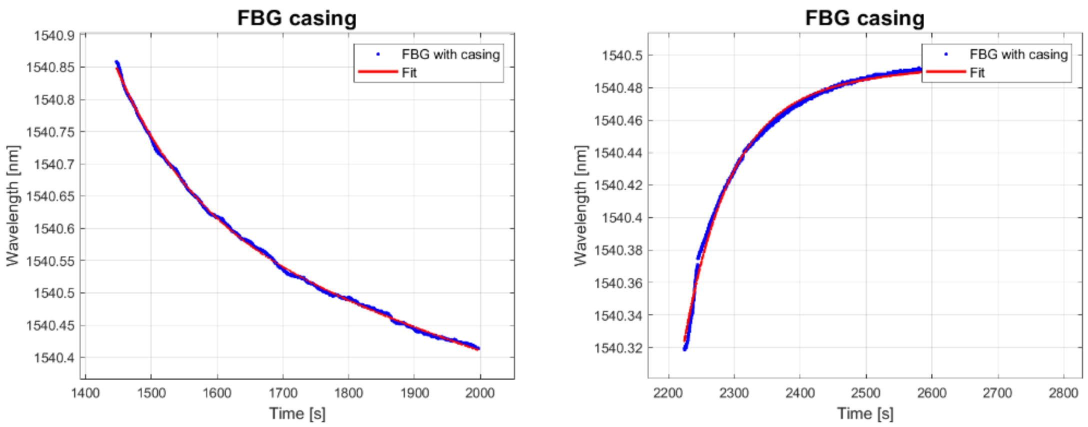

Figure 7. Transients of FBG 3 (with casing) at decreasing (left) and increasing (right) temperature

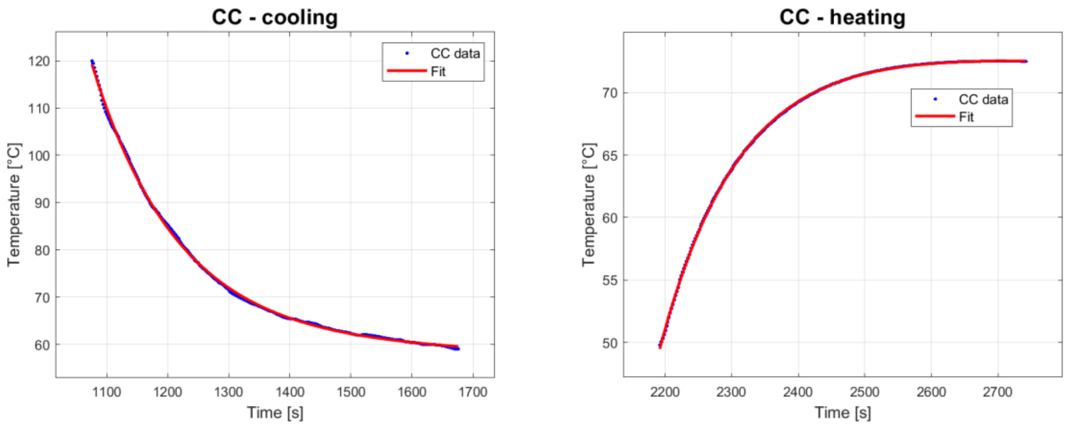

Figure 8. Transients of PT100 (chamber's sensor) at decreasing (left) and increasing (right) temperature

Comparing the measured data, it is observed that all the FBGs show a response time lower than that of the PT100. In particular, it is possible to record an extremely rapid response of the optical sensors in reading the thermal transient during the cooling and heating phases.

5. Conclusions

The outcomes of the tests presented have been highly encouraging. Several integration options for FBG sensors have been investigated, and in all cases, excellent sensitivity to rapid thermal transients has been demonstrated. This result is highly significant because it allows to benefit from the intrinsic advantages deriving from the use of optical fiber. It is now possible to create a sensing system that can provide extremely accurate data even for extremely remote components (or parts of them). FBG sensors are particularly well suited for advanced prognostic and diagnostic activities due to their minimal invasiveness, electrical passivity, and immunity to electromagnetic interference. The results of this research, in particular, suggest that these sensors could be used to detect localized overheating, for example due to overcurrent.

However, the results varied depending on the configurations examined. This suggests that the methodology for integrating and applying FBG sensors plays a critical role. As a result, additional and more in-depth analyses are required in order to define a standardised procedure capable of ensuring the levels of accuracy and reliability required by aerospace regulations.

References

[1] Safa. Kasap, *Optoelectronics and photonics : principles and practices*. Prentice Hall, 2001.
[2] X. Qiao and Q. Rong, "FBG for Oil and Gas Exploration," *Journal of Lightwave Technology, Vol. 37, Issue 11, pp. 2502-2515*, vol. 37, no. 11, pp. 2502–2515, Jun. 2019, Accessed: Feb. 10, 2023. [Online]. Available: https://opg.optica.org/abstract.cfm?uri=jlt-37-11-2502
[3] J. Van Der Horst *et al.*, "Distributed Acoustic Sensing for Downhole Production and Injection Profiling," *Journal of Petroleum Technology*, vol. 68, no. 03, pp. 78–79, Mar. 2016, doi: 10.2118/0316-0078-JPT.
[4] P. Rajeev, J. Kodikara, W. K. Chiu, and T. Kuen, "Distributed Optical Fibre Sensors and their Applications in Pipeline Monitoring," *Key Eng Mater*, vol. 558, pp. 424–434, 2013, doi: 10.4028/WWW.SCIENTIFIC.NET/KEM.558.424.
[5] U. Utzinger and R. R. Richards-Kortum, "Fiber optic probes for biomedical optical spectroscopy," *J Biomed Opt*, vol. 8, no. 1, p. 121, 2003, doi: 10.1117/1.1528207.
[6] J. A. C. Heijmans, L. K. Cheng, and F. P. Wieringa, "Optical fiber sensors for medical applications - Practical engineering considerations," *IFMBE Proc*, vol. 22, pp. 2330–2334, 2008, doi: 10.1007/978-3-540-89208-3_559/COVER.
[7] C. K. Y. Leung *et al.*, "Review: optical fiber sensors for civil engineering applications", doi: 10.1617/s11527-013-0201-7.
[8] A. A. Suryandi, N. Sarma, A. Mohammed, V. Peesapati, and S. Djurović, "Fiber Optic Fiber Bragg Grating Sensing for Monitoring and Testing of Electric Machinery: Current State of the Art and Outlook," *Machines*, vol. 10, no. 11, p. 1103, Nov. 2022, doi: 10.3390/machines10111103.
[9] "FBG | Optical products (photo devices) | Sensors & Medical Products | Products & Services | TATSUTA Electric Wire & Cable Co., Ltd." https://www.tatsuta.com/product/sensor_medical/optical/fbg
[10] G. P. Agrawal and S. Radic, "Phase-Shifted Fiber Bragg Gratings and their Application for Wavelength Demultiplexing," *IEEE Photonics Technology Letters*, vol. 6, no. 8, pp. 995–997, 1994, doi: 10.1109/68.313074.
[11] S. J. Mihailov *et al.*, "Extreme Environment Sensing Using Femtosecond Laser-Inscribed Fiber Bragg Gratings", doi: 10.3390/s17122909.
[12] "Safety through quality Efficient verification through the DO-178C life cycle."
[13] "Microsystems for Harsh Environment Testing | NIST." Accessed: Mar. 26, 2023. [Online]. Available: https://www.nist.gov/programs-projects/microsystems-harsh-environment-testing
[14] S. J. Mihailov, "Fiber Bragg Grating Sensors for Harsh Environments," *Sensors*, vol. 12, pp. 1898–1918, 2012, doi: 10.3390/s120201898.
[15] S. J. Mihailov *et al.*, "Ultrafast laser processing of optical fibers for sensing applications," *Sensors*, vol. 21, no. 4. MDPI AG, pp. 1–23, Feb. 02, 2021. doi: 10.3390/s21041447.
[16] A. Behbahani, M. Pakmehr, and W. A. Stange, "Optical Communications and Sensing for Avionics," in *Springer Handbooks*, Springer Science and Business Media Deutschland GmbH, 2020, pp. 1125–1150. doi: 10.1007/978-3-030-16250-4_36.
[17] "New Testing Methods Can Benefit Mechanical Systems." https://www.reliableplant.com/Read/28645/new-testing-methods
[18] E. J. Friebele *et al.*, "Optical fiber sensors for spacecraft applications," *Smart Mater. Struct*, vol. 8, pp. 813–838, 1999, Accessed: Feb. 01, 2023. [Online]. Available: www.iop.org
[19] R. Di Sante, "Fibre optic sensors for structural health monitoring of aircraft composite structures: Recent advances and applications," *Sensors (Switzerland)*, vol. 15, no. 8, pp. 18666–18713, Jul. 2015, doi: 10.3390/S150818666.
[20] M. Pakmehr and A. Behbahani, "Optical Exhaust Gas Temperature (EGT) Sensor and Instrumentation for Gas Turbine Engines Advanced Pressure Sensing for Gas Turbine Engines View project Intelligent systems View project", doi: 10.14339/STO-MP-AVT-306-18-PDF.

[21] I. McKenzie, S. Ibrahim, E. Haddad, S. Abad, A. Hurni, and L. K. Cheng, "Fiber Optic Sensing in Spacecraft Engineering: An Historical Perspective From the European Space Agency," *Frontiers in Physics*, vol. 9. Frontiers Media S.A., Nov. 15, 2021. doi:10.3389/fphy.2021.719441.

[22] A. Gustafsson and S. Avionics, "Fibre Optic Acquisition Systems Based on FBG Applied to Over-heat Detection for Commercial Aircraft," 2019.

[23] A. Aimasso, M. D. L. D. Vedova, and P. Maggiore, "Innovative sensor networks for massive distributed thermal measurements in space applications under different environmental testing conditions," in *2022 IEEE 9th International Workshop on Metrology for AeroSpace, MetroAeroSpace 2022 - Proceedings*, 2022. doi: 10.1109/MetroAeroSpace54187.2022.9856275.

[24] A. C. Marceddu *et al.*, "Air-To-Ground Transmission and Near Real-Time Visualization of FBG Sensor Data Via Cloud Database," *IEEE Sens J*, 2022, doi: 10.1109/JSEN.2022.3227463.