A Statistical Approach for Calibrating High Temperature Femtosecond-Laser Inscribed Fiber Bragg Grating

Manuel Jerez, Joaquín Granado, Alejandro Carballar
Electronic Engineering Department, Universidad de Sevilla (E.T.S. de Ingeniería), C/ Camino de los Descubrimientos s/n, 41092 - Sevilla, Spain; mjerez@us.es, j_granado@us.es, carballar@us.es
Correspondence: mjerez@us.es

Abstract: An end-to-end calibration method is proposed for high-temperature FBGs sensors working up to 700 Celsius. A fourth-order polynomial function reduces absolute measurement errors below 2.5 Celsius along the full operation range.

1. Introduction

The issue of measuring high temperatures has a great variety of applications nowadays, such as monitoring in concentrated solar energy plants. While two main types of Fiber Bragg Gratings (FBGs) sensors are being used to address this problem, femtosecond-laser inscribed FBGs (fs-FBFs) [1] and regenerated FBGs (RFBGs) [2], other technologies based on new materials such as sapphire, are emerging rapidly [3].

The calibration and characterization of these FBG-based sensors becomes a challenging matter, as the high precision and sensitivity needs to be maintained in a wide range of operating temperatures (from 0ºC to 1000ºC). Besides, the harsh and extreme environment applications can result in the degradation of the sensors [4]. Although being an important issue that needs to be dealt with, FBG-based sensor calibration at so high temperatures is not a trivial matter. Most of high-temperature furnaces use temperature control algorithms that make it impossible to stabilize them at a single temperature, implying the need to statistically process the data for accurate calibration of the FBG sensor. The key element in the calibration method is to obtain the unique correspondence between the measured temperature and the FBG reflected wavelength at each operating point. In this work, two different statistical methods are discussed to reach a more accurate calibration function.

2. Methodology

To perform the data acquisition for the calibration process, a fs-FBG sensor was placed inside the high temperature furnace THHR/60/250/1300 alongside with a K-type thermocouple, both joint by a platinum thread to guarantee the measurements were taken in the same spot. The fs-FBG was connected to a one-channel HBM FS22 optical interrogator, controlled via Ethernet by a PC. All the experiments have been held at CITIUS (Centro de Investigación, Tecnología e Innovación de la Universidad de Sevilla).

The selected fs-FBG sensor had a central wavelength of 1529,851nm at ambient temperature according to the spec sheet provided by the manufacturer. The data acquisitions for the calibration process were taken at ambient temperature, 50ºC, and taking steps of approximately 50ºC until reaching 700ºC. The procedure was: rise temperature of the furnace and wait for stabilization; take 50 acquisitions of the data provided by the interrogator (which would take approximately 1 minute) and take note of the temperature measurements given by the thermocouple. The data acquisition taken from the optical interrogator generated four different data files: complete optical spectrum trace, location of the FBG peaks in the wavelength range, reflected optical power measured at these peaks, and estimated temperature using the original calibration expression given by the manufacturer (which was a cubic polynomial). The wavelength shift measured at highest temperature was 9.1508nm at 709.05ºC. In Fig. 1(a), the problem of temperature oscillations at furnace operating point is shown. In Fig. 1(b), the 50 traces generated by the interrogator are superposed with the average curve generated; reflecting the need of an statistical approach to the calibration problem.

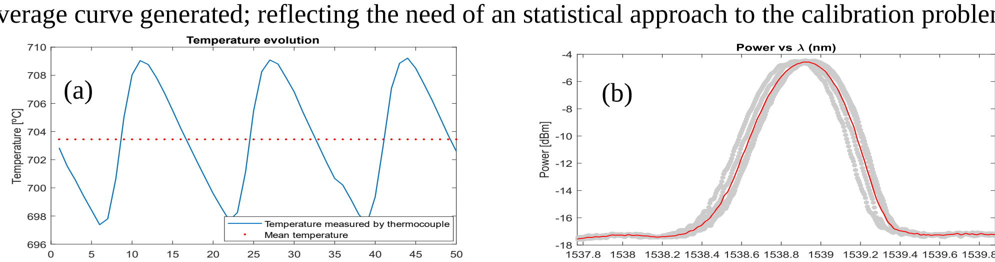

Figure 1. (a) Temperature oscillation at operating point in furnace, and (b) optical spectrum power traces generated at one acquisition and average value.

From the acquired data, two different approaches have been followed to obtain new calibration expressions with the purpose to reduce the absolute error in the temperature measurements. The first one, much simpler, would take the mean wavelength location of the power peak on each of the measuring points, as well as the mean temperature given by the thermocouple for these points. Then, it would associate each wavelength to each temperature point. Once this was done, three different polynomials (second, third and four-order) were inferred using least squared method.

The second method used for the calibration would first convert the complete optical spectrum trace from wavelength to the frequency domain and change the power units from dBm to natural units. Then, instead of taking the average values of temperature and central frequency for each of the 50 samples for each measurement point, a gaussian function would be adjusted to the samples, obtaining the temperature and optical frequency (and thus, equivalent wavelength) used to generate the calibration function. Once this was done with all the samples, best-fit polynomials (second, third and four-order) were inferred using the least squared method.

3. Results

The experiments showed a great divergence between temperatures measured by the fs-FBG sensor with the original three-degree polynomial calibration sensor compared to the temperatures measured by the thermocouple. Three polynomial calibrations were conducted with both methods, inferring polynomials with orders from 2 to 4. In Fig. 2, the absolute error between the thermocouple temperature and different calibrations are displayed against the temperature that was being measured at each point for the first (Fig. 2a) and second (Fig. 2b) methods.

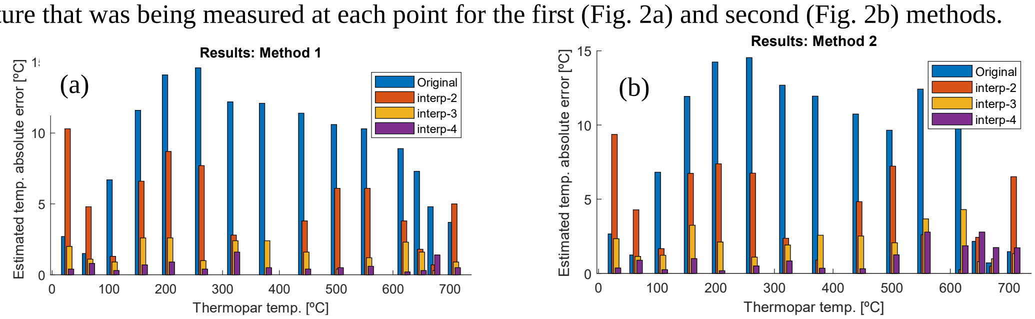

Fig. 2. Absolute error in the temperature measurements between thermocouple and original and proposed calibration expressions with the first (a) and second (b) method.

It is worth noting that the fs-FBG sensor utilized to perform the experiments had been previously used in EFECTO project [5] and were more than three years old, which could have introduced a certain degradation on the sensor and could be the explanation for the high difference between the temperatures acquired by the original calibration and the thermocouple.

The results observed above led us to conclude that the best way to calibrate the fs-FBG sensors for high-temperature measurements were obtained using a 4th-order polynomial, which gave less than 2.5ºC deviation for all the data points taken in the experiment (ranging from 24ºC to 700ºC), being the overall lowest error between all the options studied.

The use of a 4th-order calibration polynomial to obtain high-temperature measurements with FBG sensors has been proven to be necessary as well as a statistical data management to overcome limitations in the furnace temperature stability, reaching lower measurement errors than lower-order options that are widely used.

4. Acknowledgements

This work has been developed within the framework of the research projects of the Ministerio de Ciencia e Innovación, CHLOE with reference PID2021-125786OB-C22, and CATION with reference TED2021-132190B-C22; as well as the ASTERIx-CAESar project, which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement Nº 101122231.

5. References

[1] S. J. Mihailov, "Fiber Bragg Grating Sensors for Harsh Environments," Sensors 12 (2012), pp. 1898-1918.
[2] D. Barrera et al., "Packaged Optical Sensors Based on Regenerated Fiber Bragg Gratings for High Temperature Applications", IEEE Sensors Journal, 12 (2012), pp. 107-112.
[3] B. Wang et al., "Review of high temperature measurement technology based on sapphire optical fiber", Measurement 184 (2021), 109868.
[4] A. Lerner et al., "An intrinsic sensitivity calibration scheme for high temperature measurements using femtosecond point-by-point written fiber Bragg gratings", Optics & Laser technology 170 (2024), 110278.
[5] R. Rodríguez-Garrido et al., "High-Temperature Monitoring in Central Receiver Concentrating Solar Power Plants with Femtosecond-Laser Inscribed FBG", Sensors 21 (2021), 3762.