CALIBRATION AND UNCERTAINTY EVALUATION OF FIBER BRAGG GRATING TEMPERATURE SENSORS

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Abstract The spectral response of Fiber Bragg Gratings (FBGs) is highly sensitive to temperature, making them ideal for sensors in industrial, structural, and medical applications. Although FBG thermometers are more expensive and require complex interrogation systems, their immunity to electromagnetic interference makes them the preferred option in challenging environments. In such cases, FBG sensors' unique benefits outweigh their typically lower accuracy. However, there are situations where high measurement accuracy is critical. This paper focuses on using FBG-based sensors for temperature measurements where accuracy is of primary concern. It outlines a calibration setup, analyzes uncertainty sources, and describes some contributions from both the thermal and optical components of the measurement system. Experimental results show that the performance of the interrogation system depends also on the FBG's characteristics and in some cases an independent calibration of the grating and system is not sufficient to assess the overall temperature uncertainty.

Keywords: Fiber Bragg Gratings; temperature sensors; calibration; traceability

1. INTRODUCTION

In recent years, a variety of commercial temperature sensors based on Fiber Bragg Gratings (FBG) has been developed to address a wide range of applications, including the structural, industrial and medical fields, just to name the most relevant. In fact, their advantages, such as the immunity to electromagnetic fields, make the FBG-based sensors preferred, and in some cases the only viable, solution for certain demanding environments [1]. Sensors based on FBGs have been developed in various shapes, configurations, and materials, but they all rely on the sensitivity of the spectral response – in particular of the peak wavelength, the so-called Bragg wavelength – to temperature. However, FBGs also exhibit a remarkable cross-sensitivity to strain, which is typically nullified encapsulating the sensing portion of the fiber in rigid embodiments, although also bare FBGs are employed to sense temperature [2] when minimal invasive impact or fast response are required. A priori knowledge of the sensor model can only offer qualitative insight into the temperature measurement [3]. Manufacturer specifications provide nominal parameters, such as the spectral peak wavelength and sensitivity at a reference temperature, and specific calibration coefficients according to a polynomial model. When stated, the uncertainty, is commonly reported as the maximum error within defined time and temperature intervals. This may work for most of the applications, but when the required uncertainty is lower than 1 °C, any single sensor must be properly calibrated before its usage. To this aim, conventional temperature sensor calibration methods can be applied, similar to those used for traditional electrical sensors [4], [5]. However, since FBGs are fiber optic sensors, they have specific characteristics and subtle source of uncertainties that must be carefully analyzed and accounted for both during the calibration and the sensor usage.

2. METHODS

The setup employed in this work is based on a commercial sensor calibrator (Fluke 9142 field Dry-Well) that contains an isothermal block whose temperature can be controlled from -25 °C to 150 °C. The dry-block hosts both the optical sensors and a reference temperature sensor to ensure the metrological traceability.

The reference temperature device is a secondary-level standard four-wires Pt100 sensor. The calibration uncertainty of the reference sensor is 60 mK (coverage factor k=2) and its resistance is measured with a 6.5 digits multimeter.

A simpler thermal setup was also implemented using a temperature-controlled breadboard (Thorlabs PTC1), which is more affordable and thus more likely to be available in many laboratories. In this case the sensor under calibration was inserted in a custom isothermal block made with copper, firmly fixed on the breadboard surface, and isolated from the ambient using a thick polystyrene layer. A low-cost class AA Pt1000 sensor made in thin-film technology was employed as a reference sensor. The setup is similar to that presented in [6]. The simplified setup demonstrated to have similar performance in term of accuracy of the commercial dry-well, although in a reduced temperature range from +15 °C to +45 °C and with some limitations for the sensor dimensions.

Different interrogation systems, also called Fiber Bragg Gratings Analyzers (FBGA), were investigated and tested in term of accuracy, resolution, speed, noise, stability. The results reported in this paper concern two analyzers, namely A1 and A2 which are based on different technologies: A1 is a swept laser source and A2 is spectrometer based on a diffraction grating. The analyzers employed in this work have a physical resolution of 10 pm and 166 pm, respectively.

As an example, two FBGs S1 and S2 having different characteristics in term of reflectivity and FWHM (Full Width Half Maximum) were calibrated and afterwards tested. S1 is commercial FBG with high reflectivity and a FWHM of 0.24 nm. The second FBG S2 was manufactured in our laboratories with a femtosecond laser using the Point-by-Point (PbP) method and it has a FWHM of 0.45 nm.

The calibration was carried out by setting the dry-block temperature from -10 °C to 80 °C in 10 °C steps. For each step, the temperature measured from the reference sensor and the wavelength returned by the FBGA were recorded. The calibration was repeated several times in order to assess repeatability and reproducibility effects. The relationship between temperature and wavelength was approximated as a

second order polynomial function whose coefficients were obtained with a fitting algorithm. In this way the full measurement chain, composed by the sensor, the interrogation system and its peak tracking algorithm, was fully calibrated.

3. PRELIMINARY EXPERIMENTAL RESULTS

The residual fitting errors are shown in Fig. 1 for the four different combinations analyzer/sensor.

Analyzer A1 provides the best results while there is a not so evident difference between the two sensors. According to this test, uncertainty is mainly related to the analyzer and the maximum error is of about 20 ÷ 30 mK for A1 and about 80 ÷ 100 mK when the analyzer is A2.

But FBG sensors have other sources of uncertainty that need to be assessed, such as the effect of the fiber length, the optical signal intensity, and the dependence on the polarization state, just to list the most relevant ones.

These sources have an effect on the measurements and must be taken into account when calibrating and using the sensor.

In order to test the sensitivity to the optical signal intensity, a mechanical attenuator was introduced between the sensor and the interrogation system A1 in order to reduce the light intensity in a controlled way. Both FBGs have been kept at constant temperature during the test, but the signal intensity was reduced from -15 dBm to -35 dBm. An apparent temperature change was recorded during the test as shown in Fig. 2.

The sensor S2, having small reflectivity and large FWHM shows, a maximum error of about 0.2 °C which is due to the peak prominence that decreases with the intensity thus affecting the peak tracking algorithm results. However, the error with sensor S1 is much smaller but still not negligible with respect to the fitting contribution.

Results obtained with analyzer A1 do not depend on the polarization state since the analyzer embeds a depolarizer, but measurements with analyzer A2 are much more sensitive to the fiber bending and routing and these errors are more evident when PbP FBGs are employed. On the other hand, analyzer A1 is sensitive to the fiber length. As an example, in our setup a fiber length of 25 m introduces an error larger than 1 °C that must be compensated.
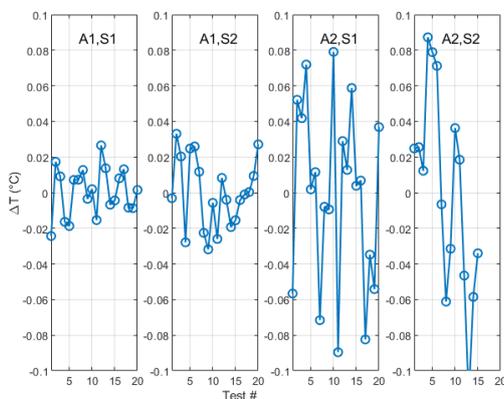

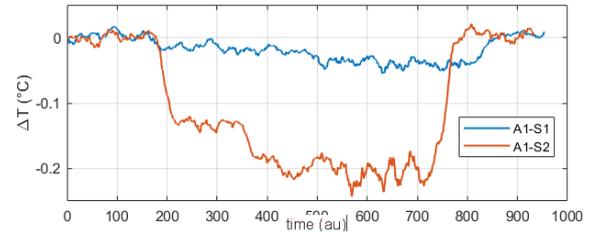Figure 1. Residual fitting error obtained with different analyzers and sensors.

Figure 2. Test at constant temperature changing the optical signal intensity introducing attenuations of 0 dB, 5 dB, 10 dB, 15 dB and 0 dB.

4. CONCLUSIONS

The calibration and use of FBGs as temperature sensors present issues that are not typically addressed when calibrating traditional electrical sensors. The technology of the interrogation system and the grating writing method have significant effects on the measurements, and these effects cannot be evaluated simply performing a standard multi-step calibration procedure. Measurement traceability with these thermometers therefore requires specific calibration procedures, as well as the identification and analysis of influence quantities unique to this technology.

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