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Evaluating Fiber Bragg Grating Technologies for High Temperature Sensing in Concentrated Solar Power Plants

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Abstract: Femtosecond-inscribed versus regenerated FBGs are compared for temperature sensing in Concentrated Solar Power applications. Experiments up to 1000°C demonstrate fs-FBGs' superior performance, requiring recalibration for optimal CSP integration.

1. Introduction

The development of optical sensors in recent years has been intrinsically linked to major advances in Fiber Bragg Gratings (FBGs), which have established themselves as one of the most widespread technologies for temperature measurement in extreme environments [1]. In this context, their potential application as temperature sensors in Concentrated Solar Power (CSP) receivers emerges as a viable option to overcome the extreme conditions, exceeding 1000°C and experiencing extremely high radiation levels, present in these renewable energy generation systems [2]. While sapphire FBGs are currently gaining prominence in such high-temperature applications [3], two FBG fabrication techniques are extensively implemented: femtosecond laser-inscribed FBGs (fs-FBGs) [4,5] and regenerated FBGs (rFBGs) [4,6]. This work presents a comparison of these two technologies and evaluates their performance in a tubular furnace at temperatures up to 1000°C, discussing their suitability for CSP applications.

2. Methodology

For the comparison, none of the sensors had ever been used. The fs-FBGs were manufactured by Engionic (https://engionic.de/), and in this article, two such sensors embedded in an array within a steel capillary will be tested. These sensors were calibrated up to 700°C using a fifth-degree polynomial. The two regenerated sensors were manufactured by the company CalSens (https://www.calsens.es/). Of these, one was integrated into a steel capillary, while the other was in an alumina capillary; both were calibrated up to 1050°C using a fourth-degree polynomial. For the experiments, each fs-FBG sensor was placed with one of the rFBG in a THHR/60/250/1300 furnace along with a K-type TC K 003 thermocouple, used as the reference temperature. All were joint using a platinum wire to ensure spatial consistency. All experiments were conducted at the Research, Technology and Innovation Center of the University of Seville (CITIUS). The furnace procedure consisted of progressively increasing the temperature to 1000°C, maintaining stable sensor conditions at intermediate points. Upon reaching 1000°C, the temperature was decreased to 750°C, followed by a subsequent increase back to 1000°C. Additionally, sensor characterization was performed at ambient temperature to analyze their optical properties.

3. Results

Before discussing the results related to the experiments conducted in the furnace, it is pertinent to analyze the levels and shapes of the reflected power from the different sensor types. In Fig. 1a, the power trace resulting from combining an array of three fs-FBGs with the r-FBG inscribed in steel using an optical splitter is presented. It is evident that the power reflected by the femtosecond laser-inscribed sensors is several orders of magnitude higher than that of the regenerated sensor. Additionally, Fig. 1b provides a detailed view of the reflected shape for each sensor, highlighting that the fs-FBG exhibits a significantly more uniform response compared to the rFBG. This enhanced regularity improves measurement robustness by providing a well-defined reference point for spectral shift detection.

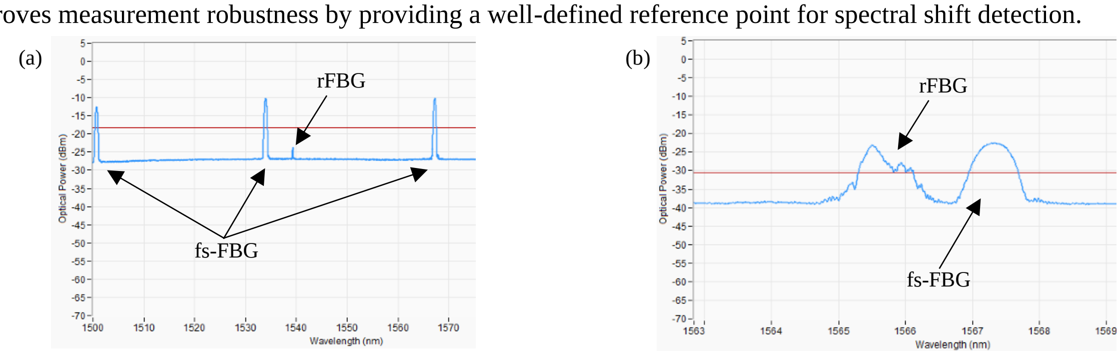

Fig 1. (a) Power trace of 3 fs-FBGs and a rFBG combined with an splitter; (b) detail of the reflected power curve from a fs-FBG and a rFBG.

Regarding the results obtained in the furnace, these are presented in Fig. 2. First, we analyze the spectral shift in Fig. 2a, where the spectral shift of one of the fs-FBGs is contrasted with that of the steel rFBG. In this case, the rFBG exhibits a slightly lower spectral shift, specifically 0.3 nm less at the highest evaluated temperature of 985°C. A lower spectral shift would allow for a greater number of sensors to be connected to the same interrogator, given its fixed spectral range. However, this difference is not significant enough to be considered a decisive advantage. Fig. 2b and 2c showcase the accuracy in the measurements given by optical sensors against the reference temperature, defined as the relative error between the temperature measured by the different FBGs and the thermocouple.

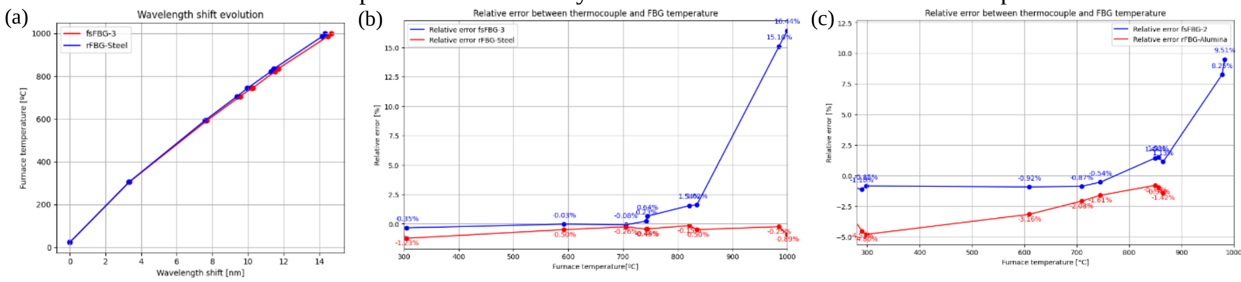

Fig. 2. (a) Spectral shift of the different FBGs during the experiments, (b) relative error between fs-FBG and steel rFBG against thermocouple and (c) relative error between fs-FBG and alumina rFBG against thermocouple

Several comments can be made from these figures. First, all sensors generally exhibit good performance, with the fs-FBGs and the steel rFBG standing out, showing errors below 2% across all of their respective calibrated ranges. Among them, the femtosecond laser-inscribed FBGs present lower error values for temperatures below 700°C. The alumina rFBG is notable because, despite using the same technology as the steel rFBG, it shows significantly higher errors, likely due to the fragility of the material and potential physical damage. Finally, it is evident that for fs-FBGs to function correctly at the highest temperature range, recalibration would be necessary.

4. Conclusions

The conducted study has demonstrated that it is possible to achieve consistent and accurate temperature measurements up to 1000°C using both femtosecond inscribed and regenerated FBGs. However, fs-FBGs would require recalibration to extend their operational range and ensure measurement accuracy. Within the overlapping temperature range of both sensor types, the two fs-FBGs provided better results than the rFBGs when compared to the reference thermocouple. This improvement may be attributed to the use of a higher-degree polynomial, which better aligns with the sensor's physical behavior. Among the two regenerated FBGs, the one embedded in the steel capillary exhibited measurements closer to those of the thermocouple. Regarding potential application in CSP systems, fs-FBGs appear to be the more suitable choice due to their ability to integrate multiple sensors within a single fiber, optimizing spatial multiplexing, reducing equipment requirements, and lowering costs. Additionally, their significantly higher reflected power and power shape compared to regenerated FBGs would enable prolonged operation under extreme conditions, as they would require greater degradation before reaching failure.

5. Acknowledgements

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