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Fiber Specklegram Sensors sensitivities at high temperatures

L. Rodriguez-Cobo*, M. Lomer, J.M. Lopez-Higuera

Photonics Engineering Group, University of Cantabria, 39005, Santander (Spain)

ABSTRACT

In this work, the sensitivity of Fiber Specklegram Sensors to high temperatures (up to 800ºC) have been studied. Two multimode silica fibers have been introduced into a tubular furnace while a HeNe laser source was launched into a fiber edge, projecting speckle patterns to a commercial webcam. A computer generated different heating and cooling sweeps while the specklegram evolution was recorded. The achieved results exhibit a remarkably linearity in FSS's sensitivity for temperatures under 800ºC, following the thermal expansion of fused silica.

Keywords: High temperature, Speckle patterns and optical fiber sensor.

1. INTRODUCTION

Optical fiber sensors have been proved as reliable technology to quantify many different measurands [1] such as strain, vibration, temperature… Among others, those optical fiber sensors based on interferometric approaches, typically exhibit remarkable sensitivities for specific scenarios [2]. Several interferometric techniques have been reported to determine the thermal properties of materials under high temperatures such as Fabry-Perot, Michelson or Mach Zehnder among others[2]. These techniques exhibited a high accuracy and dynamic range when teste over flat solid samples, however, they usually require extremely high precision in their optical assembly and, for many scenarios, these methods may result too large.

Some limitations of the classical interferometric approached described can be solved employing Fiber Specklegram Sensors (FSSs), which have overcame during last years because of the cost reduction in electronics and the computer capacity increase. In a simple way, a Fiber Specklegram Sensor employs the result of an interference between propagated modes through a fiber to quantify the changes in their propagating mean: the multimode optical fiber. Depending on the optical parameters of both fiber and source, the sensitivity of FSSs can be controlled, making the measurement of many parameters possible such as: strain, vibration or temperature [3]. Although, with a proper choosing of light source and sensing fiber, the sensitivity to specific parameters can be improved, isolating the final sensor system from undesired noise; in particular scenarios, this noise has to be removed using advanced processing techniques [4].

As commented, FSSs have been widely employed to measure mechanical variations [3], however, their application to temperature sensing is very limited. In [5], different direct comparison processing techniques have been employed to measure the temperature variations in FSSs but the achieved results have been limited only to a few degrees due to the FSSs dynamic range limitation [3].

In this work, the sensitivity of Fiber Specklegram Sensors implemented using multimode silica fibers has been evaluated at very high temperatures (reaching 800 ºC). Different parameters that have influence on final FSSs sensitivity at high temperatures have been discussed and compared to the experimental data. Two commercial multimode silica fibers have been employed for several controlled temperature ramps, while a HeNe excited their speckle patterns to be recorded by a low-cost camera. The achieved results establish a reference point to employ this interferometric technique to measure very high temperatures.

2. SENSING PRINCIPLE

As FSSs employ a mechanical support as sensing element (typically a multimode fiber), it suffers from different phenomena that provoke changes in the projected specklegram both mechanical and optical. As described in [6], the optical sensitivity of a FSSs can be simplified by Eq. 1:

$$S_{Optical} \propto I_S \cdot C_S \cdot N_S \propto I_S \cdot {L_C}/{\lambda^2} \tag{1}$$

where I_S is the specklegram total intensity (related to the incoming power), C_S is the specklegram contrast (which is related
*luis.rodriguez@unican.es

to the coherence length of the source L_S) and the number of speckles ($N_S \approx 2a\pi\, NA/\lambda^2$) which is proportional to the core radius (a) and to the Numerical Aperture (which also varies with the refractive index). Assuming the specklegram intensity (I_S) and contrast (C_S) constant, the optical sensitivity of FSSs is related to the number of modes, which is modified by the core radius (a) and by variations on the refractive index (by changing NA).

According to [7], the refractive index variation for silica and close to the HeNe wavelength is $\Delta n_{eff} \approx 0.7\%$ around 800ºC (being $\Delta NA \propto \Delta n_{eff}$) and assuming the coefficient of thermal expansion as constant on radial direction, the number of modes (N_S) is scaled by this value in $\Delta a \approx 0.6 \cdot 10^{-6}$. However, this optical speckle sensitivity is only produced in the area affected by the heat source, modifying the speckle interference only in that area. These optical modifications may vary the final sensitivity of the FSSs, because they are not reproduced at not heated fiber locations (such as the detecting edge) but modifying the interference may produce sensitivity variations, increasing the sensor residual noise.

Beyond optical modifications, the coefficient of thermal expansion also provokes a linear deformation which modifies the speckle patterns and whose variations (in terms of intensity difference) can be employed to quantify the desired measured [4] as strain variations (Eq.2):

$$\Delta I_S \propto K \cdot \Delta\varepsilon \tag{2}$$

where ΔI_S is the absolute value of the intensity difference between two specklegrams which can be considered proportional (K) to the applied deformation ($\Delta\varepsilon$), but only for weak perturbations [4] (that keep the specklegram at the same modal state, allowing a direct comparison).

Since specklegram fluctuations provoked by optical modifications are confined to the heated area, most of them are not propagated through the detecting device (the refractive index and the core radius are the originals out of the heating area). Besides, since the heated fiber length (several centimeters) produces an intensity variation much higher than the optical fluctuations, last ones can be understood as noise present in FSSs, assuming the intensity difference only proportional to temperature with a different proportionality constant.

Different experiments based on two commercial silica fibers have been employed to analyze the thermal sensitivity of FSSs at high temperatures.

3. DATA PROCESSING AND EXPERIMENTAL SETUP

As commented before, one weak point of FSS is its limitation regarding its dynamic range. When the perturbation to be measured is too high, a direct comparison between intensity of specklegrams is not useful. In this scenario, where only the sensitivity of FSSs to high temperature is analyzed, the differential processing method is employed, to isolate the results from other undesired contributions.

Differential process is based on computing the intensity variations between specklegrams under similar (weak) perturbations, assuming the fiber to be at the same modal state. The differential value between two specklegrams (i and j) reflects their mean difference per pixel (Eq. 1).

$$D\{i,j\} = \frac{1}{K \cdot N \cdot M} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \left| I_{nm}^i - I_{nm}^j \right| \tag{1}$$

where K is the full scale value of the specklegram color map (e.g. K = 255 for 8-bit grayscale) and $I_{n,m}^i$ corresponds to the pixel of the n,m position of the i-th specklegram of N by M pixels. Based on this method, the mean intensity difference per pixel between specklegrams of similar temperatures is computed, translating the temperature increase into intensity variation, thus, FSS sensitivity can be obtained.

A tubular furnace (Carbolite MTF/12/38/250) has been employed to obtain the specklegram sequences. A heating ramp controlled by a computer has been applied to the fiber under test, while a HeNe laser source was launched into the fiber, projecting speckle patterns at fiber end, where a low-cost webcam (640x480 px) has been attached. The experimental setup is detailed in Fig. 1:
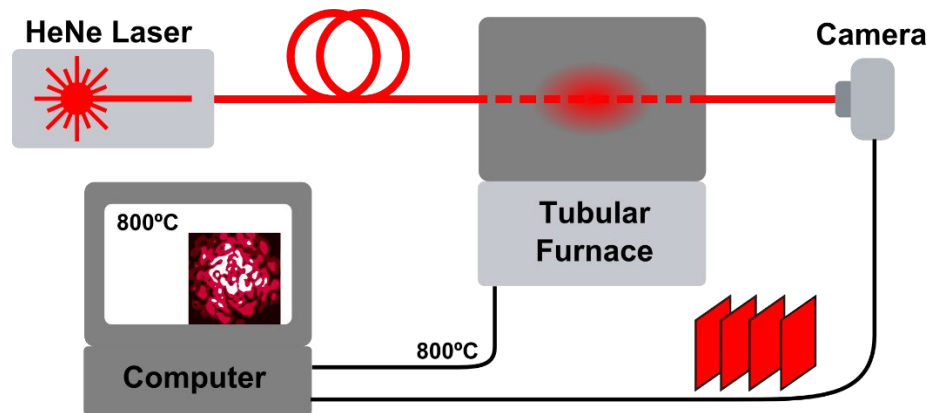
Figure 1. Setup employed for the characterization. Tested fibers were passed through the tubular furnace while a temperature ramp was applied, modifying the projected specklegrams.

Employing the setup described in Fig. 1, two commercial silica fibers have been tested: a 62.5 um standard multimode fiber of Draka Comteq and a 100 um core multimode fiber of Corning (100 / 140CPC). Both fibers have been heated from 100 °C up to 800°C recording their projected specklegrams each 15 seconds, to allow a direct comparison between them. Several increasing and decreasing ramps have been applied to each tested fiber, to evaluate the system repeatability.
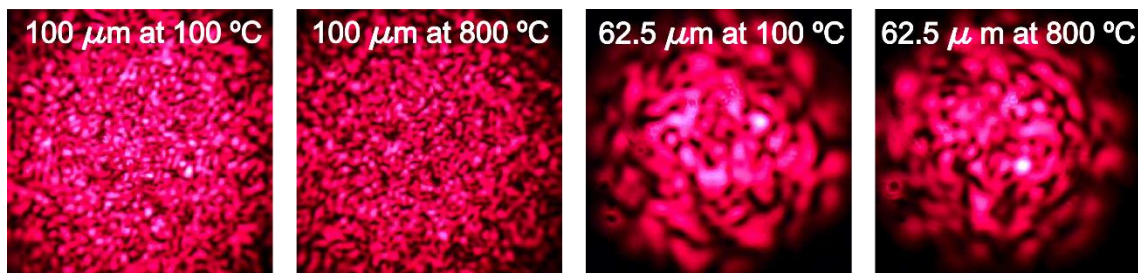

Figure 2. Captured specklegram of both tested fibers at 100 and 800 °C. The resolution of processed specklegram has been set to 400 by 400 pixels to increase their sensitivity.

In Fig. 2, some examples of the processed specklegrams are depicted. The power of the HeNe laser launched into the fiber has been trimmed to achieve similar specklegram intensities at camera side (where capturing properties have been maintained), in order to remove the intensity factor of the final sensitivity. Anyway, the processed sequences have been intensity-normalized to deal with slight power fluctuations due to fiber loses.

4.   ACHIEVED RESULTS

Several heating and cooling sweeps have been applied to both fibers. The differential processing scheme has been applied to obtain the sensitivity of each fiber at different temperatures. The cumulative value of these differential values has been also computed, to obtain a look-alike relation between speckle variations and temperature increase, however, this value is only the addition of several small steps, thus, the temperature cannot be obtained directly only using a specklegram as reference. In this work, only the sensitivity of FSSs to high temperatures have been studied, and the cumulative value is just for illustration. However, to overcome this limitation, a full dynamic range FSS can be obtained by applying advanced processing techniques [4]. Both sensitivities and their accumulated value have been depicted in Fig. 3. Several specklegrams have been captured at each temperature and averaged before computing the difference to the previous specklegram in order to reduce the final noise.
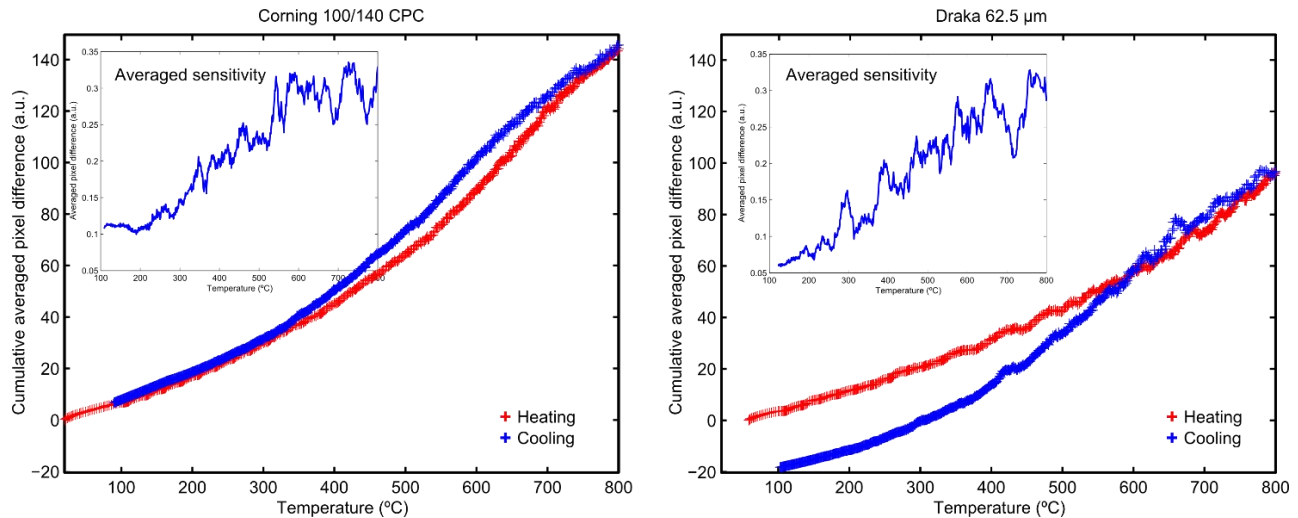
Figure 3. The sensitivity and its accumulated valued (Cumulative averaged pixel difference) have been of both tested fibers.

As detailed in Fig 3. both fibers exhibit a linear sensitivity increase with temperature that matches to the thermal expansion of fused silica for temperature under 1000 ℃ [8]. However, the 100/140 fiber shows a higher sensitivity that cannot be explained from the mechanical silica differences but, it indeed can be explained by the speckle sensitivity to optical properties. The amount of speckles comprised in specklegrams projected by the Corning fiber is much higher than the projected by the Draka fiber (as shown in Fig. 2), that, despite the intensity normalization, leads to a higher optical sensitivity to external perturbations [6]. Besides, the Corning fiber exhibits a good response in terms of hysteresis which suggest a remarkable mechanical stability up to the tested temperatures. On the other hand, the Draka fiber shows a worse reputability during the cooling sweep which suggest a worse mechanical response at high temperatures, beyond the residual errors associated to the sensor scheme.

5. CONCLUSIONS

In this work, the sensitivity of Fiber Specklegram Sensors (FSSs) at very high temperatures (800℃) has been evaluated employing two commercial multimode silica fibers. The sensitivity has been obtained by averaging different specklegram captured at the same temperature before computing a differential value with the previous captured frames. A tubular furnace controlled using a computed has been employed to perform several heating-cooling sweeps while the projected specklegrams have been captured using a commercial webcam. The same optical power of a lab-quality HeNe laser source has been launched into the tested fibers to reduce sensitivity errors. The achieved results exhibited a linear sensitivity increase with temperature, according to the evolution of thermal expansion of fused silica at temperatures under 1000℃. The proposed study can be the basis to develop a full-range high temperature sensor based on specklegrams. This work has been supported by the project TEC2013-47264-C2-1-R.

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