Multiplexed regenerated fiber Bragg gratings for high-temperature measurement

G. Laffont, Romain Cotillard, Pierre Ferdinand

Multiplexed regenerated fiber Bragg gratings for high-temperature measurement

G Laffont[1], R Cotillard[1] and P Ferdinand[1]

[1] CEA, LIST, Laboratoire de Mesures Optiques, Gif-sur-Yvette cedex, F-91191, France

Abstract

A high-temperature gradient of a conventional tubular furnace is characterized using a single-fiber sensing line with wavelength-multiplexed short-length-regenerated fiber Bragg gratings. The multiplexed gratings are simultaneously regenerated using a high-temperature annealing process. Temperature calibration from ambient temperatures up to 900 °C is conducted leading to a standard deviation of 0.15 °C after the polynomial fitting of the wavelength shift with the temperature.

1. Introduction

Fiber Bragg gratings (FBGs) are well-established strain, temperature and pressure transducers finding numerous applications in many scientific and industrial fields. For metrological applications, the use of FBGs in harsh environments, especially in the case of continuous monitoring under high temperature, is limited due to the ageing of their main optical characteristics (Bragg wavelength drift, decrease in reflectivity). The long-term use of FBG transducers at temperatures beyond 400–500 °C is a challenging task and becomes a major research topic. Among the various solutions considered to develop temperature-resistant FBGs and thus increase their operating lifetime [1], the regeneration process of type-I seed FBGs photowritten in a standard single-mode fiber is a fruitful approach [2]. The so-called regenerated FBGs not only exhibit excellent stability of their reflectivity up to l295 °C [3] but also present a spectral shape of the Bragg peak similar to that of type-I gratings, thus preserving the spectral accuracy desirable to get transducers with the appropriate metrological performances.

Regeneration is an exciting and attractive approach which dramatically increases the operating lifetime of FBGs operating in a very high temperature environment, thanks to glass material thermal engineering at the nanometer scale. Regenerated FBGs are a technological breakthrough for high-temperature sensing, opening the way to many applications. Some of them require the adaptation of the regeneration process in order to realize sensing lines with transducers spaced by only a few millimeters. The use of draw tower gratings has been proposed to realize the arrays of regenerated gratings [4, 5]. In order to increase the reflectivity of spectrally multiplexed regenerated FBGs very close to each other and thus get an optimal signal-to-noise ratio for the Bragg wavelength measurement, we have chosen to photowrite strong seed gratings using a conventional interferometric setup and then to simultaneously regenerate all the gratings.

In this paper, we present first the annealing setup used to regenerate the multiplexed FBG sensing line. Then we detail the topology of the sensing line and the regeneration process. Temperature calibration over an 850 °C wide range is performed and its application to the temperature gradient reconstruction of a conventional tubular furnace is demonstrated.

2. Photowriting and regeneration setup

2.1. Seed FBG photowriting

Aiming at regenerating the sensing line with a dense array of FBGs and getting optimal reflectivity, we use a Lloyd interferometric setup to photowrite and multiplex spectrally strong seed FBGs. The Lloyd mirror and photowriting process are illustrated in figure 1, showing the blue luminescence of a hydrogen-loaded SMF-28 fiber illuminated by the CW 244 nm light emitted by a frequency-doubled argon ion laser (FreD Innova 300). The seed gratings used in this study are photowritten in a H_2-loaded SMF-28 fiber (100 bar, 2 weeks, 20 °C). This fiber has been chosen to benefit from its low confinement factor in order to optimize the reflectivity of the regenerated gratings [6]. The seed gratings are saturated and their length is equal to 2 mm thus leading to Bragg peaks having a full-width-at-half-maximum of 2 nm. The short length of the seed gratings together with the available power density once the laser beam is focused onto the fiber's core leads to a long inscription time, roughly 2 h per grating. In a single fiber, ten multiplexed seed gratings are written over three days. Between each inscription, the fiber is replaced under hydrogenation but the diffusion kinetics of hydrogen within the fiber at room temperature is obviously not fast enough to recover the initial photosensitivity. Optimized seed gratings arrays could be obtained using a different laser to reduce the inscription time and thus to reduce the hydrogen desorption between consecutive gratings. Femtosecond IR gratings could be an alternative as their regeneration in silica fiber has already been demonstrated [7].

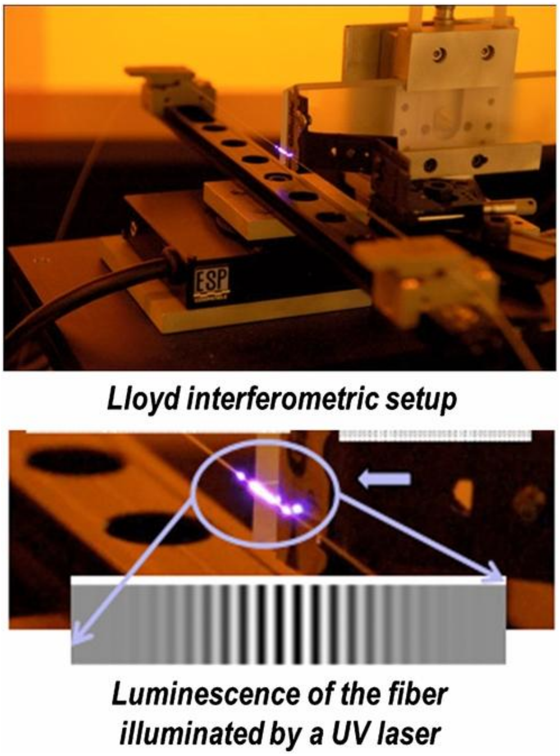

Figure 1. Photowriting of a seed FBG using a Lloyd mirror interferometer.

2.2. FBG regeneration setup

A vertical tubular calibration furnace (TCl200, TecKnow) is used to anneal the FBGs which are introduced in an 8 mm diameter ceramic insert to homogenize the temperature inside the furnace (see figure 2). Between 400 and 1000 °C, the furnace stability is given to be ±0.5 °C and the type-N thermocouple (TC) precision is ±1 °C. In the regeneration experiment, the TC is adjacent to the seed FBG in order to control the temperature experienced by the grating during the thermal treatment. As we are using a vertical tubular furnace, the fiber cannot be analyzed in transmission. Thus, the spectral behavior of the FBG is monitored in reflection by a spectrometer. Even after using a flattened amplified spontaneous emission (ASE) source for the FBG monitoring, the residual fluctuation of the spectral power density complicates the direct normalization of the FBG-reflected signal during heating ramp. High-temperature processing of the silica fiber degrades its mechanical resistance and removes its coating (either polyimide or acrylate). Thus the multiplexed seed FBGs are packaged in a metallic capillary prior to the regeneration to avoid any subsequent bare fiber manipulation.

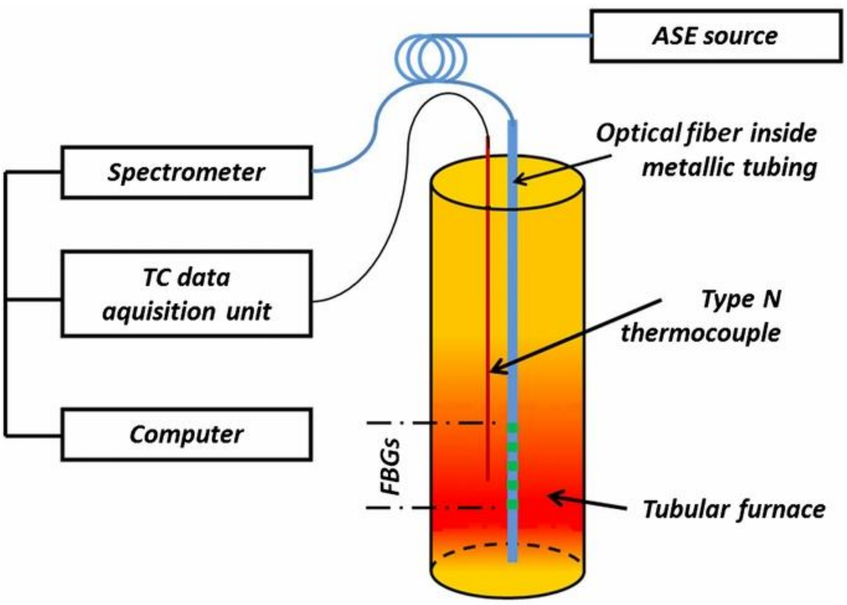

Figure 2. Annealing setup for FBG regeneration.

3. Simultaneous regeneration of multiplexed FBGs

3.1. Topology of the multiplexed sensing line

The Bragg wavelengths of two consecutive seed FBGs are spectrally spaced by 5 nm to avoid spectral overlapping during temperature gradient characterization. We have realized a line comprising ten multiplexed FBGs separated by 5 mm each. The tabulated Bragg wavelengths at room temperature are given in table 1.

Grating	FBG 1	FBG 2	FBG 3	FBG 4	FBG 5	FBG 6	FBG 7	FBG 8	FBG 9	FBG 10
λ_{Bragg} (nm)	1527.5	1532.5	1537.4	1542.4	1547.3	1552.0	1556.9	1561.9	1566.7	1571.6

Table 1. Bragg wavelengths of the seed fiber Bragg gratings at room temperature.

The whole length of the sensitized fiber is 47 mm. Before the regeneration experiments, the temperature gradients within the central heating zone of the furnace have been characterized (see figure 3). The seed gratings are positioned in a central area with the temperature homogeneity of ±1.5 °C at 710 °C and ±3.5 °C at 920 °C and over a length of 7 cm.

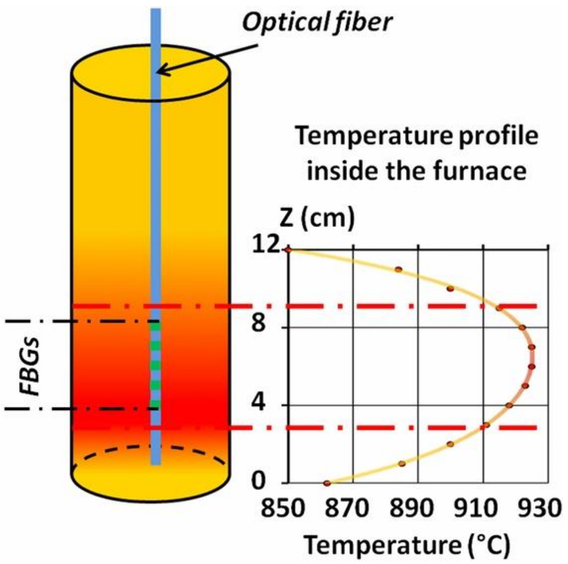

Figure 3. Temperature gradient within the heating zone used for the regeneration process.

3.2. Regeneration protocol

During the regeneration process, the seed FBGs are pre-annealed at an intermediate temperature of 710 °C for two hours. Then the furnace's temperature is raised to 920 °C, which is the point triggering the regeneration for all the multiplexed seed FBGs. This point is chosen slightly above the lowest regeneration temperature for that fiber (~900 °C) in order to alleviate the decrease in temperature along the multiplexed seed FBGs due to the furnace's gradient. At 710 °C, the seed FBG reflectivity exhibits a slight decrease together with a decrease in its full-width-at-half-maximum. Once the temperature is raised to 900 °C, the reflectivity quickly decreases: after 15 min, the seed grating is fully erased. Then the reflectivity starts to increase again and reaches an optimal level after one hour. Heating is stopped and the temperature decreases. A regenerated FBG is obtained (see figure 4). The process is similar in the case of multiplexed seed FBGs as shown in figure 5 (right). The main difference arises from the heterogeneity in the reflection signal between gratings due to the lack of normalization versus the source spectral shape.

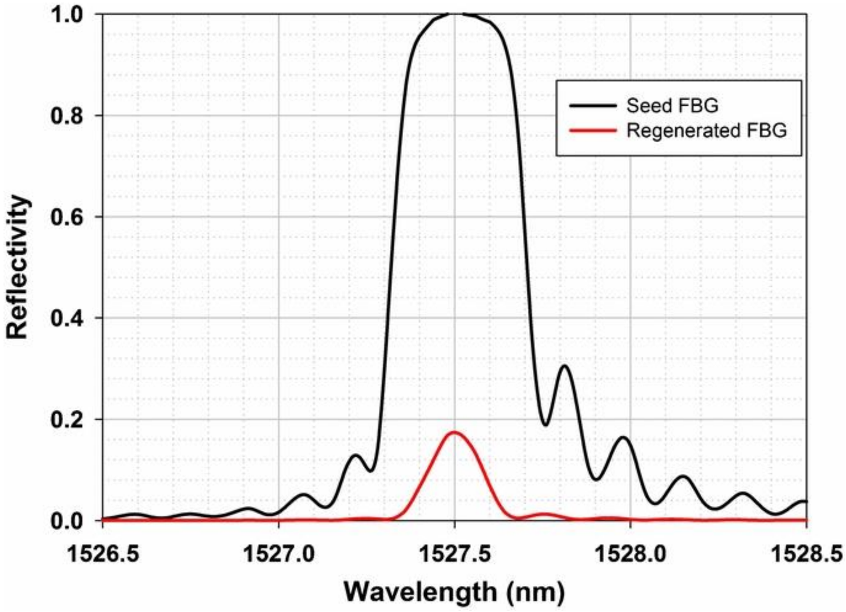

Figure 4. Spectrum of a seed FBG and that of the corresponding regenerated FBG (both spectra acquired at room temperature).

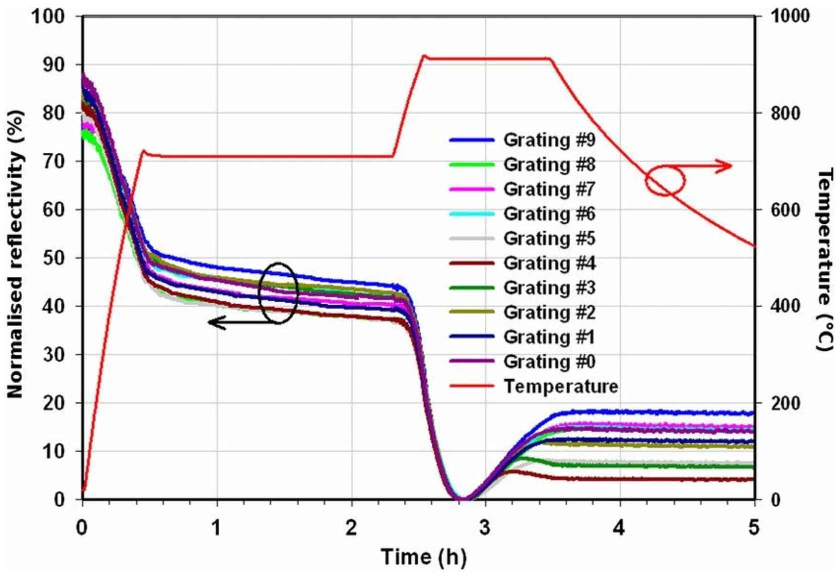

Figure 5. Evolution of the reflection signal from the ten multiplexed seed FBGs regenerated simultaneously.

4. Application to high-temperature gradient characterization

Due to their temperature stability demonstrated up to 1295 °C, regenerated FBGs are attractive transducers for high-temperature monitoring. As the spectral shape of the regenerated gratings Bragg peak is similar to that of a type-I grating, good metrological performance is expected. Thus, these transducers seem particularly useful for continuous high-temperature monitoring. The availability of a multiplexed dense sensing line is of great interest for high-temperature gradient mapping. But accurate temperature measurements require us first to calibrate the sensing head accurately.

4.1. Temperature calibration

The sensing line of ten 5 mm spaced multiplexed regenerated FBGs is calibrated in temperature over the range of 50–900 °C. The optical setup is described in figure 2 and comprises: (i) an ASE optical source covering both C and L bands and incorporating a gain flattening filter (flatness to ±1.2 dB) and (ii) an optical spectrum analyzer configured in order to get a 50 pm spectral resolution (wavelength accuracy of ±50 pm over C+L band and level flatness to wavelength specified by the manufacturer as ±0.3 dB). A type-N TC is used to obtain the temperature in the middle of the sensing area while the ten FBGs are positioned in the high-temperature furnace central zone having a temperature stability of ±1 °C. The temperature is raised to 900 °C and then heating is stopped and the temperature gently decreases. TC temperatures and FBG spectra are acquired in parallel by one point every 5 s. Measurements are post-processed in order to retrieve the Bragg wavelengths and to synchronize both spectral and temperature measurements. Due to a logarithmic decrease of the furnace's temperature during cooling, we have fitted the experimental data according to the following procedure. First, the Bragg wavelength and the temperature acquired are averaged over small ranges δT of temperature, typically over 5 °C. The elementary step δT is chosen in order to get at least one experimental Bragg wavelength over each interval. Then the averaged data are fitted using a fifth-order polynomial curve and we obtain a 0.15 °C of standard deviation over this 850 °C range (see figure 6). This method operates like a comb in temperature selecting subsets of experimental points to be averaged. In figure 7, the advantage of this method before applying a fit is illustrated. At high temperatures, a standard polynomial fit directly applied to the experimental data is not robust enough in order to avoid deviation above 850 °C. In contrast, fitting the data averaged over small windows of width δT = 5 °C leads to a more robust result, facilitating the computation of the thermal sensitivity of regenerated gratings over a wide temperature range. Moreover, with such a width of 5 °C, no significant bias is observed with regards to the experimental data.

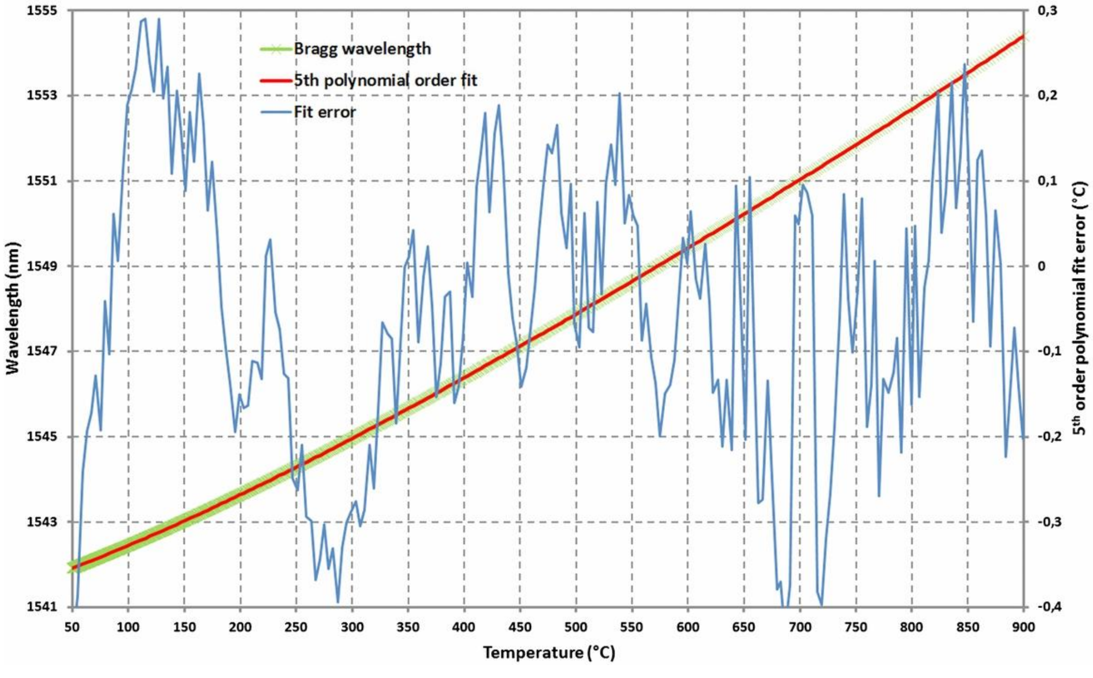

Figure 6. Fifth-order polynomial fit of the Bragg wavelength over a range of 850 °C.

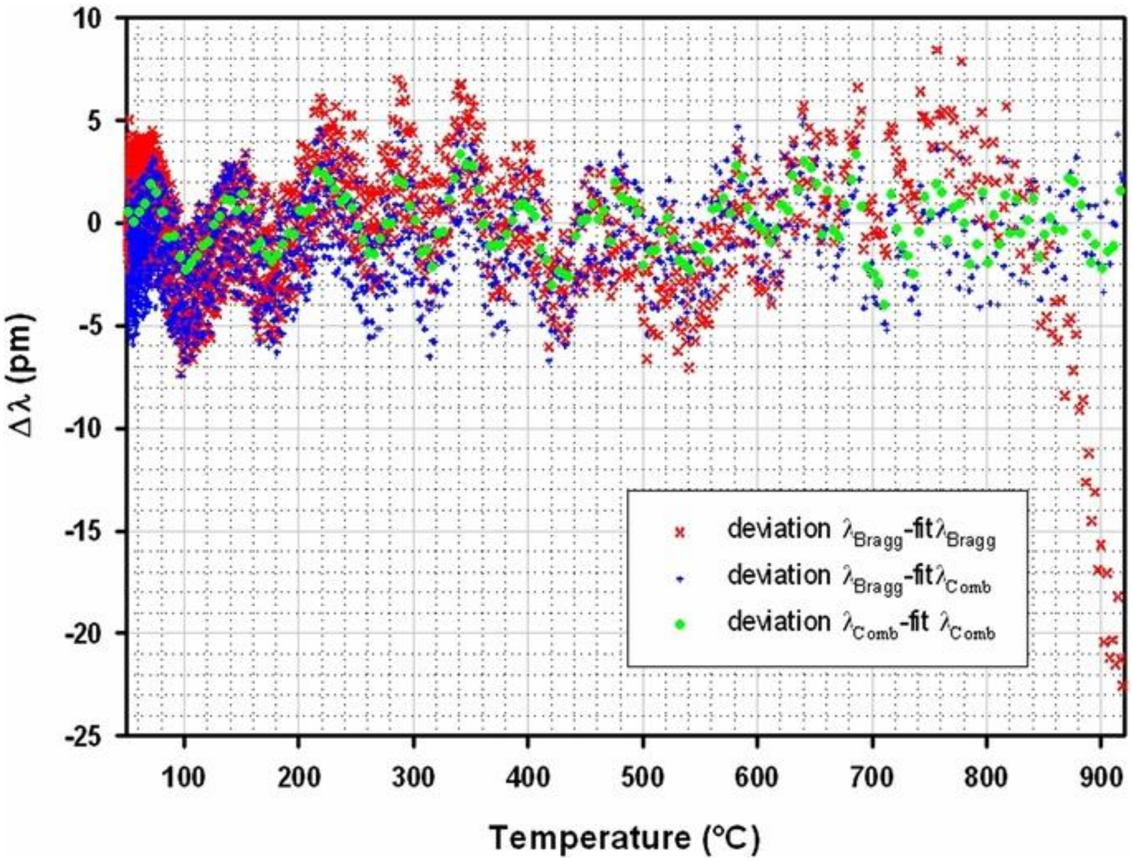

Figure 7. Deviations between the experimental Bragg wavelengths with regard to a fifth-order polynomial fitting processed on averaged (blue point, subset averaged every 5 °C) and non-averaged (red point) data. The green points stand for the error between the averaged data and the polynomial fit computed thereon.

4.2. High-temperature gradient mapping

To illustrate the potential of wavelength multiplexed regenerated FBGs array, we use the sensing line comprising ten transducers to characterize the vertical temperature gradient of a high-temperature vertical tubular furnace. The sensing fiber is inserted within a metallic capillary hermetically sealed at its extremity. The capillary is used to package the sensing array and protect it during manipulation, while, in that experiment, the sealed extremity also prevents any air movement around the fiber that may decrease the measured temperature. For the purpose of comparison, a type-N TC is positioned at the same location as the regenerated FBG closed to the capillary's sealed extremity. The bundle with the TC and the packaged array of regenerated FBGs is translated toward the upper part of the furnace by seven steps of 1 cm each. Temperatures measured both by the TC and by the regenerated FBGs are plotted in figure 8. Both profiles are in good agreement: the main discrepancy arises from the measurements in the deepest area of the furnace due to a positioning error of the capillary. A better guiding of the sensing head during translation may improve the results. Gradients up to 130 °C cm^{-1} are measured. Beyond the illustrative purpose, this result also suggests the need for a regenerated FBG array with a greater length to avoid any translation process for temperature profile mapping.

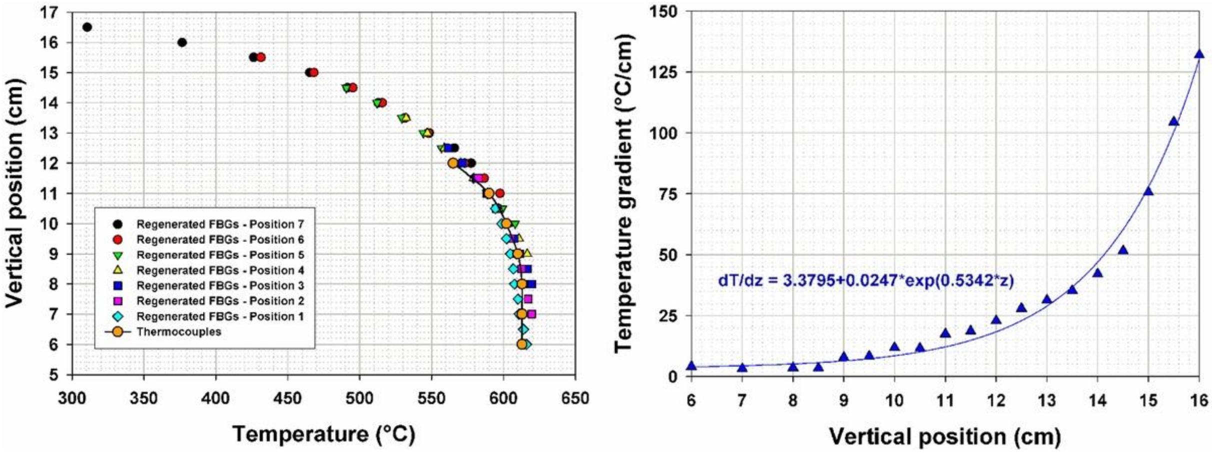

Figure 8. Temperature profile and gradient of the tubular furnace reconstructed by an array of ten multiplexed regenerated FBGs.

5. Conclusion

The thermal processing of fiber Bragg grating (FBG) photowritten in the conventional single-mode SMF-28 silica optical fiber, the so-called regeneration process, opens the way to a rich and innovative field of applications of FBG transducers for severe environments, especially those involving very high temperatures up to 900 °C. The adaptation of the thermal annealing setup used to regenerate seed FBGs to the case of wavelength-multiplexed seed FBG array enables the use of a single sensing line to map, for instance, high-temperature profiles in real time without any translation of the probe. In this paper we have demonstrated the realization and testing of a dense sensing head made up of ten short-length (2 mm) multiplexed regenerated FBG transducers realized on a single fiber with reflectivity between 10% and 30% and spatially spaced by 5 mm. This sensing line has been used to characterize the temperature gradient of a tubular furnace operated at 610 °C and over a length of 10 cm. Simultaneous temperature calibration of the multiplexed line has been achieved with a standard deviation of 0.15 °C and over a wide temperature range (50 °C; 900 °C). Coming improvements will consist of both increasing the temperature stable length of the furnace used to regenerate and calibrate the regenerated FBG array and in improving the inscription process in order to reduce the inscription time. These regenerated FBG arrays will trigger numerous applications in various industrial sectors (steel industry, power plant, nuclear reactor, oil and gas, oil refining units, turbines, aircraft engines...).

References

[1] Pal S et al. 2003 Characteristics of potential fibre Bragg grating sensor-based devices at elevated temperatures Meas. Sci. Technol. **14** 1131–6

[2] Canning J et al. 2009 Regenerated gratings J. Eur. Opt. Soc. Rapid Publ. **4** 09052

[3] Canning J et al. 2008 Extreme silica optical fibre gratings Sensors **8** 6448–52

[4] Lindner E et al. 2009 Arrays of regenerated fiber Bragg gratings in non-hydrogen-loaded photosensitive fibers for high-temperature sensor networks Sensors **9** 8377–81

[5] Lindner E et al. 2011 Post-hydrogen-loaded draw tower fiber Bragg gratings and their thermal regeneration Appl. Opt. **50** 2519–22

[6] Bandyopadhyay S et al. 2011 A study of regenerated gratings produced in germanosilicate fibers by high temperature annealing Opt. Express **19** 1198–206

[7] Cook K et al. 2012 Regenerated femtosecond fibre Bragg gratings Proc. SPIE **8351** 835111