Simultaneous temperature and strain measurement based on arc-induced long-period fiber gratings

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ABSTRACT

A compact sensor able to discriminate between temperature and strain related effects was implemented. The proposed sensing head comprises a single long-period grating with two sections written consecutively in the SMF-28 fiber, by the electric arc discharge technique, using different fabrication parameters. The sensor performance is based on the distinct temperature and strain sensitivity values presented by two neighbor resonances belonging to each grating section. The temperature and strain resolutions are ± 0.1 ºC and ± 40 με, respectively.

Keywords: Temperature measurement, strain measurement, optical fiber sensors, fiber gratings, long-period gratings, electric arc discharge

1. INTRODUCTION

Long-period fiber gratings (LPFGs) have been used as sensing elements in the simultaneous measurement of temperature and strain[1-4]. Potential drawbacks of the proposed sensing schemes are the requirement for two optical sources, the use of polarized light and/or polarization maintaining fibers and the need for two distinct fiber types. Recently, it was demonstrated that the response of arc-induced gratings to applied strain and temperature could be controlled by changing the fabrication parameters[5]. Based on the properties of those gratings, a sensor head comprising two concatenated LPFGs was implemented to perform temperature and strain measurements. However, to avoid recoupling between the two gratings an index matching gel was used, which limits the range of the working temperature. A possibility to surpass this problem is recoating the region between the gratings, but it could be a risky alternative since this process can break the fiber, and do not help to reduce the overall length of the sensing head, which could be undesirable for some applications.

In this paper we present a compact sensor head which overcomes the previous drawbacks. The sensor consists of a LPFG with two sections, which have the same period and different fabrication parameters, written consecutively in the SMF-28 fiber, i.e., without physical separation in between.

2. EXPERIMENTAL RESULTS AND DISCUSSION

To implement the sensor head, a LPFG was written in the SMF-28 Corning fiber using the electric arc technique[6]. The fabrication parameters (fiber pulling tension, *T*; electric current, *I*; arc duration, *t*; period, *Λ* and the number of discharges, *N*) were chosen according to the requirement of having two neighbor resonant wavelengths in the third

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telecommunication window showing different sensitivities to strain and temperature. To achieve this result a previous study on the influence of the fabrication parameters on the properties of the arc-induced LPFGs[7] was taken into account. As far as the gratings spectra are concerned, it was concluded that the increase of the electric current or of the arc duration shifts the spectra towards lower wavelengths, whilst the increase of the fiber pulling tension leads to an opposite shift of the resonances. Simultaneously, an increase of those parameters contributes to the fabrication of gratings with deeper resonances.

The results given below correspond to the 4^{th} resonance of LPFGs with a period of 540 μm. Figures 1 and 2 summarize the effect of the fabrication parameters on the sensitivity of the gratings for changes in the applied strain and temperature.

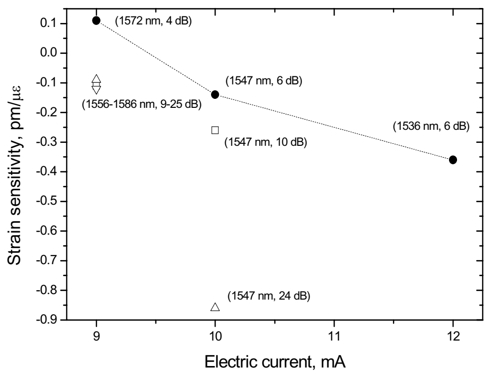

Fig. 1 Strain sensitivity of 540 μm-LPFGs as a function of the electric current (in brackets: resonant wavelengths and attenuation of the loss-peaks).

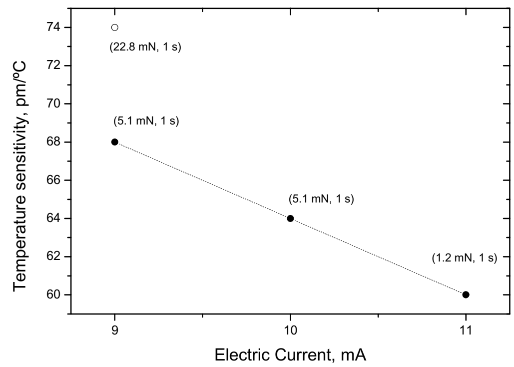

Fig. 2 Temperature sensitivity of 540 μm-LPFGs as a function of the electric current (in brackets: pulling tension and arc duration).

As it can be seen, the strain sensitivity can be changed considerably from +0.11 to –0.36 pm/με, when the electric current increases from 9 to 12 mA. In Fig. 1, the points joined have similar attenuation losses and were obtained for three different arc electric currents, therefore showing the effect of this parameter on the sensitivity of the gratings to strain. This figure also suggests a possible dependence, under certain experimental conditions, of the strain sensitivity on the attenuation of the loss-peaks. For example, for a current of 10 mA and peaks with an attenuation ranging from 6 to 24 dB, there is a change in sensitivity from –0.14 to –0.86 pm/με. On the other hand, the temperature sensitivity can be changed from 68 to 60 pm/ºC (for temperatures up to 110 ºC), when the electric current increases from 9 to 11 mA (Fig. 2). It is also noticed that the pulling tension considerably changes the temperature sensitivity. Moreover, as will be

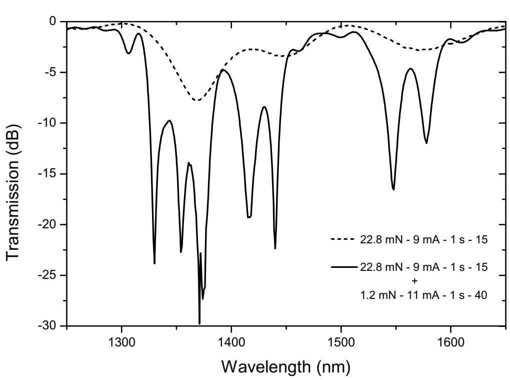

Fig. 3 Evolution of the grating spectrum during the fabrication process.

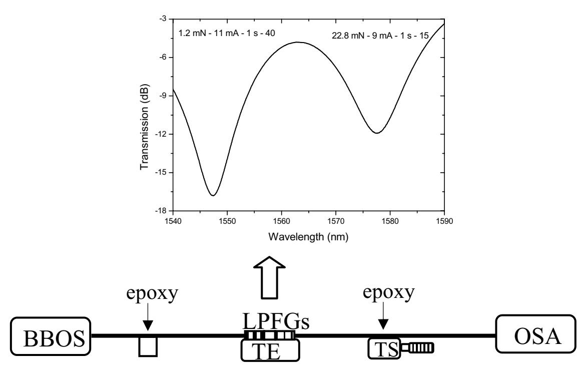

Fig. 4 Grating transmission spectrum and experimental set-up.
a) Close-up of the two resonances under measurement.
b) Experimental set-up for characterization of the sensing head. BBOS: broadband optical source; OSA: optical spectrum analyzer; TEC: thermoelectric cooler; TS: translation stage

discussed below, the quadratic dependence of the resonant wavelengths on temperature becomes more pronounced with the increase of the electric current.

Fig. 3 shows the transmission spectrum of the grating after the writing process of each section. Following the inscription of the first section (*T*=22.8 mN, *I*=9 mA, *t*=1 s, *Λ*=540 μm and *N*=15), these writing parameters were modified and the second section (*T*=1.2 mN, *I*=11 mA, *t*=1 s, *Λ*=540 μm and *N*=40) was written without physical separation in between.

The proposed technique for simultaneous strain and temperature determination is based on the wavelength shift measurement of the two central wavelength resonances in Fig. 4a when temperature or strain is changed. The resonance at longer wavelength corresponds to the one obtained during the writing of the first section which continue to evolve afterwards, whilst the resonance at shorter wavelength appears due to the second section. During the writing process of the second section, the resonance at longer wavelength changes its amplitude and bandwidth. Firstly, the amplitude increases; secondly the bandwidth becomes greater; thirdly, the resonance starts to split in two, the larger and shorter wavelength ones being related to the first and second sections, respectively. The experimental setup used for characterization of the sensor is shown in Fig. 4b. To calibrate the system, strain in the range of 0-1600 με was applied at constant temperature, and by keeping the strain constant the temperature was changed in the range of 22-110 ºC. The corresponding calibration results are presented in Fig. 5-6.

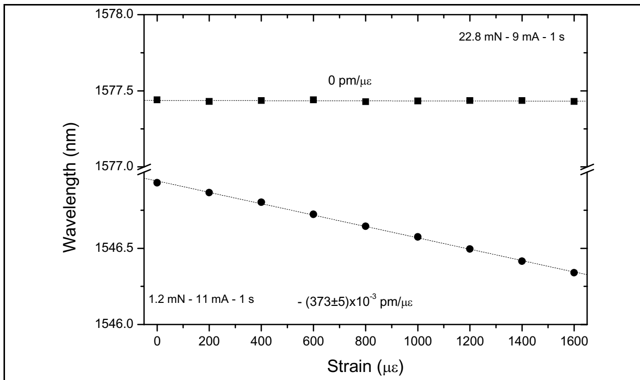

Fig. 5 Strain response of the sensor head.

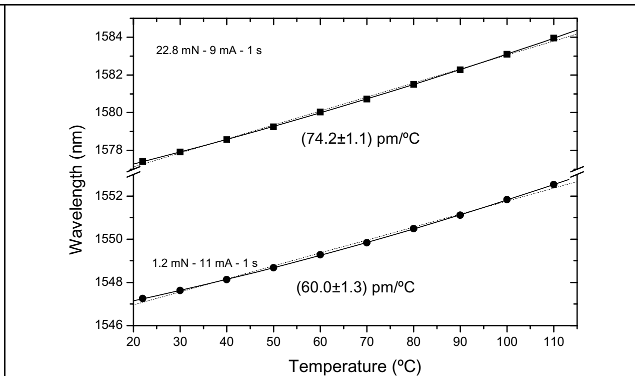

Fig. 6 Temperature response of the sensor head.

It is interesting to note that the resonance at longer wavelengths is insensitive to strain. Also important is the fact that the dependence of the resonant wavelengths on temperature becomes increasingly parabolic with the increase of the electric current. This non-linear dependence, up to ~700 ºC, was reported in previous works[6-8].

In what follows a linear dependence is assumed to calculate the matrix coefficients[1]. From the results obtained (the slopes of the linear fittings), the matrix equation (1) that allows the simultaneous measurement of strain and temperature can be written as:

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = 36.1x10^{-3} \begin{bmatrix} 0 & 0.373 \\ -74.2 & 60.0 \end{bmatrix} \begin{bmatrix} \Delta \lambda_1 \\ \Delta \lambda_2 \end{bmatrix}, \tag{1}$$

where $\Delta\lambda_1$ and $\Delta\lambda_2$ are expressed in pm, ΔT in ºC and $\Delta\varepsilon$ in με. To improve the system performance, corrections were further made in order to compensate for deviations between linear and quadratic behavior. To execute this, the quadratic and the linear equations for the temperature responses of both resonances are taken. For each temperature change a correction factor, which consists of the difference between the quadratic and the linear functions, is subtracted from the original wavelength values, enabling more precise measurand information.

The system resolution was estimated directly from the calibration procedure. The *rms* deviations corresponding to temperature and strain were found to be ± 0.1 ºC and ± 40 με, respectively (Fig. 7).

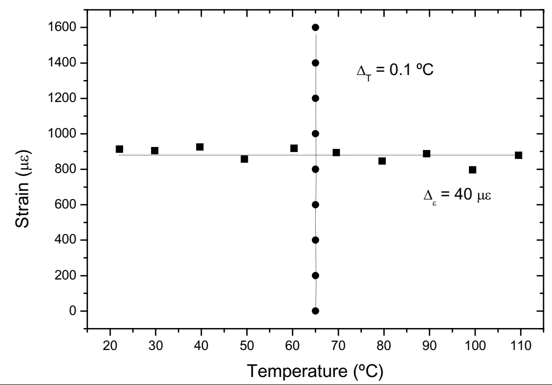

Fig. 7 Sensor output as determined by Eq.1, after compensation for the quadratic behavior.

3. CONCLUSION

An arc-induced LPFG in the SMF-28 fiber consisting of two consecutive sections with equal period but other different fabrication parameters was produced. The transmission spectrum of the written grating exhibited two neighbor resonances having distinct temperature and strain sensitivity values. Based on such responses, a sensor was implemented for the simultaneous measurement of those physical quantities. The proposed sensor presented corresponding resolutions of $\pm$ 0.1 ºC and $\pm$ 40 με.

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