Simultaneous Measurement for Strain and Temperature Based on a Long-Period Grating Combined With a High-Birefringence Fiber Loop Mirror

O. Frazão, L. M. Marques, S. Santos, J. M. Baptista, and J. L. Santos

***Abstract*—This work presents an alternative solution for simultaneous measurement of strain and temperature. The sensing head is formed by a long-period fiber grating combined with a high-birefringence fiber loop mirror resulting in a configuration capable of temperature and strain discrimination. These optical devices have opposite sensitivity responses when a variation of temperature and/or strain is applied. Maximum errors of $\pm 0.8\ ^\circ$C and $\pm 21\ \mu\varepsilon$ are reported over 60 $^\circ$C and 700-$\mu\varepsilon$ measurement ranges, respectively.**

***Index Terms*—Fiber-loop mirror, long-period grating (LPG), optical fiber sensors, strain-temperature discrimination.**

I. INTRODUCTION

A long-period grating (LPG) is based on a fiber core refractive index modulation with a periodicity in the range of several hundred micrometers [1]. The operation principle behind this type of grating is a large modulation period which promotes the optical coupling between the propagating core mode and copropagating cladding modes.

The LPG devices have been very valuable both in optical communications as in fiber sensing. In this last field, they have proved to be effective sensing elements of different measurands, such as temperature, transverse load, strain, curvature, pressure, refractive index, etc. [2].

Bhatia *et al.* demonstrated a possible sensing head based on LPGs for simultaneous measurement of strain and temperature [3]. The differential modulation of the attenuation bands in LPGs is used and the resonance bands were located at wavelengths of 1332 and 1607 nm, respectively. On the other hand, Han *et al.* [4] have demonstrated a sensing head with two LPGs where opposite temperature sensitivities are obtained by controlling the doping concentrations of the GeO_2 and B_2O_3. Recently, arc-induced LPGs with opposite strain sensitivities were fabricated by using different arc discharge electric currents [5]. Other configurations for simultaneous measurement of strain and temperature based on LPGs combined with fiber Bragg gratings were proposed by Patrick *et al.* [6] and Guan *et al.* [7].

In this work, we present a configuration for strain and the temperature discrimination. The setup combines an LPG with a high-birefringence fiber loop mirror (HB-FLM). Due to the opposite sensitivity response of the HB-FLM compared with the LPG relatively to strain and temperature, it is possible to obtain a sensing head for strain and temperature discrimination.

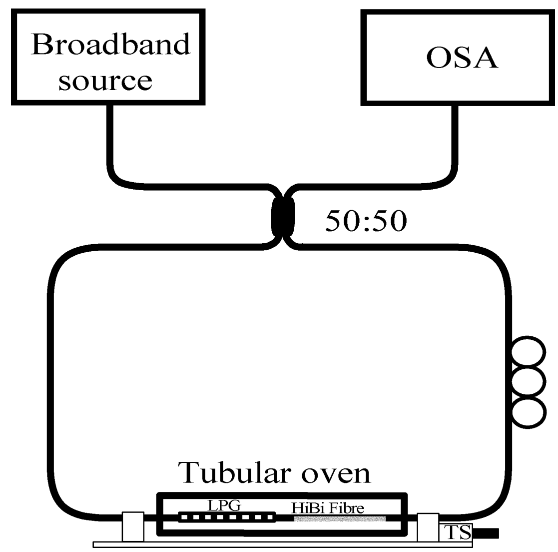

Fig. 1. Experimental setup.

II. PRINCIPLE AND EXPERIMENTAL SETUP

Fig. 1 presents the experimental setup which consists in an optical broadband source, a fiber-loop mirror, containing an LPG and a section of high-birefringence (HiBi) fiber and an optical spectrum analyzer (OSA) with a resolution of 0.05 nm. The optical source is an erbium-doped broadband source, with a central wavelength of 1550 nm and a spectral bandwidth of 100 nm, and has the purpose of characterizing the sensing head.

The HB-FLM is formed by a 3-dB (2×2) optical coupler with low insertion loss, an optical polarization controller (PC),

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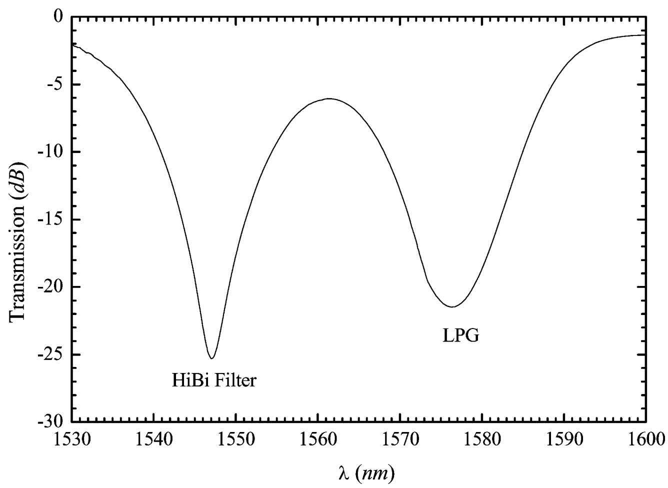

Fig. 2. HB-FLM and LPG spectral representation.

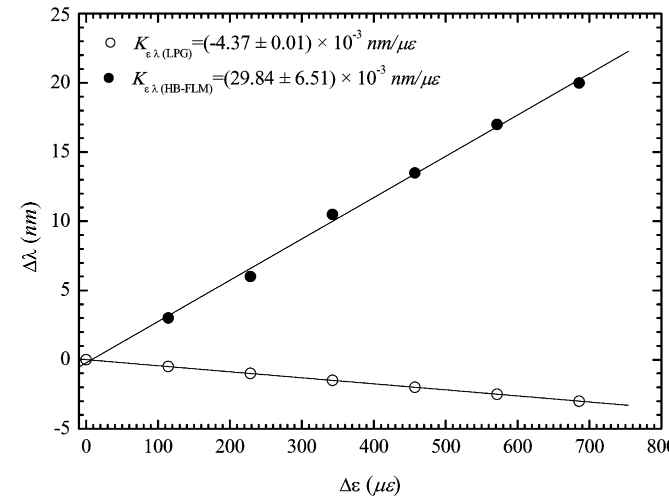

Fig. 3. Strain response of the sensing head.

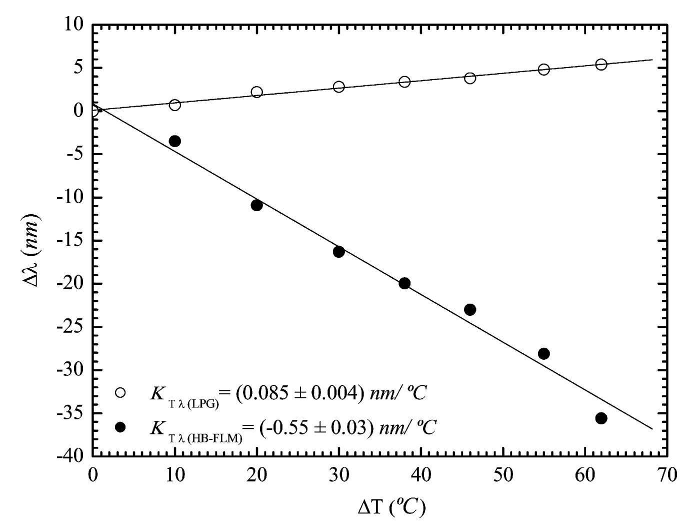

Fig. 4. Temperature response of the sensing head.

and a HiBi fiber section. This HiBi fiber (3M FS-PM-7621) is a polarization-maintaining single-mode optical fiber (internal elliptical cladding) for the wavelength of 1550 nm with a beat length of 1.6 mm at 633 nm and an attenuation of 1.0 dB/Km.

The fiber loop mirror acts like a bandpass filter for the input signal as it can be seen in Fig. 2. The input light is split into two counterpropagating beams, which transverse the loop, by means of the 3-dB coupler. The PC changes the polarization state of both clockwise and counterclockwise beams. After the PC, the slow or fast axis of the two counterpropagating beams is exchanged to fast or slow axis and experiences a smaller or larger refractive index, respectively. The phase difference between beams that propagate with different states of polarization is proportional to the HiBi fiber length, resulting in constructive and destructive interference. This interference is given by recombination of both rotated lights at the coupler and can be seen in the filter response. Therefore, the loop filter characteristic is similar to an unbalanced Mach–Zehnder and can be used as a sensor [8]. The length used for the HiBi fiber was approximately 45 mm with the filter spectral width of $\Delta\lambda = \lambda^2/\beta L$, where λ is the average wavelength and β and L, the birefringence and the length of the HiBi fiber, respectively. The $\Delta\lambda$ is approximately 97 nm. This value was determined considering that only one minimum of the HB-FLM was required and desired to prevent the overlapping with the LPG minimum.

The sensing head for strain and temperature discrimination is based on a combination of the HB-FLM and an LPG. The LPG was fabricated in a Corning SMF-28 fiber, by means of electric arc discharge with a period $\Lambda = 405$ μm and length $L \approx 20$ mm. During grating inscription, the fiber, under a tension of 5.1 grams, was subjected to 48 arc discharges with 9 mA of current and 1 s of duration. The resulting resonance wavelength of the LPG was 1578 nm. With the PC, it was possible to optimize the HB-FLM for a wavelength of 1547 nm with maximum loss of 25 dB.

III. Experimental Results

The sensing head was attached to a translation stage with a resolution of 1 μm and placed in a tubular oven, which permits the temperature of the sensing head to be set with an error smaller than 0.1 °C.

Figs. 3 and 4 show the evolution of the wavelength shift $(\Delta\lambda)$ of the LPG and HB-FLM when the sensing head is subject to strain and temperature variation, respectively.

The strain and temperature sensitivity responses of the HB-FLM are opposite to the LPG. They shift in opposite directions when temperature or strain variation is applied. As expected, the LPG presents a small variation when compared with the HB-FLM [2]. The negative slope of the temperature sensitivity of the HB-FLM can be explained by the effect that temperature changes have on the internal lateral stress magnitude and, therefore, on the fiber birefringence. The increase in temperature will decrease the birefringence and will increase the beat length [9]. With strain the opposite occurs, corresponding to an increase in birefringence.

When temperature and strain applied to the sensing head vary, the filter and LPG wavelengths are shifted according to $\Delta\lambda_i = K_{Ti}\Delta T + K_{\varepsilon i}\Delta\varepsilon$, where ΔT and $\Delta\varepsilon$ are temperature and strain variation, respectively, and $i = 1, 2$ corresponds to the HB-FLM and the LPG, respectively. This permits us to write a well-conditioned system of two equations for ΔT and $\Delta\varepsilon$ given in a matrix

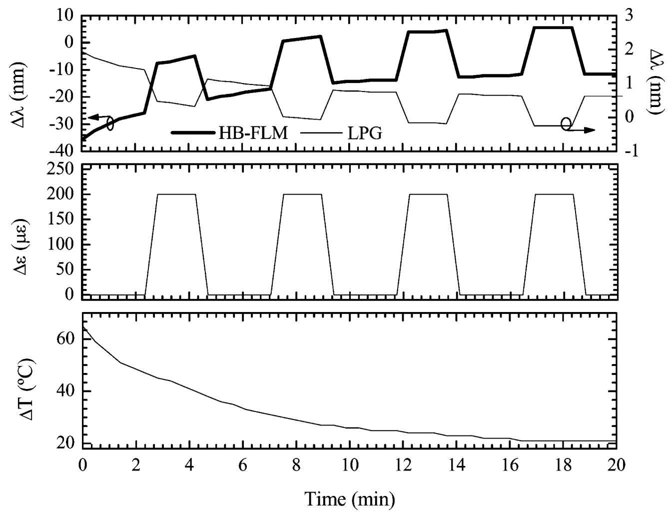

Fig. 5. Sensor output for simultaneous change of strain and temperature.

form as

$$\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix}=\frac{1}{D}\begin{bmatrix}K_{\varepsilon \mathrm{HB-FLM}} & -K_{\varepsilon \mathrm{LPG}}\\ -K_{T\mathrm{HB-FLM}} & K_{T\mathrm{LPG}}\end{bmatrix}\begin{bmatrix}\Delta\lambda_{\mathrm{LPG}}\\ \Delta\lambda_{\mathrm{HB-FLM}}\end{bmatrix} \tag{1}$$

where the determinant is $D = K_{T\ \mathrm{HB-FLM}}K_{\varepsilon\ \mathrm{LPG}} - K_{\varepsilon\ \mathrm{HB-FLM}}K_{T\ \mathrm{LPG}}$. The thermal sensitivity $(K_{T\ \mathrm{HB-FLM}}, K_{T\ \mathrm{LPG}})$ and strain sensitivity $(K_{\varepsilon\ \mathrm{HB-FLM}}, K_{\varepsilon\ \mathrm{LPG}})$ are the sensor head sensitivity coefficients. The matrix coefficients are obtained from the experimental slopes shown in Figs. 3 and 4, resulting in

$$\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix}=\frac{1}{16.8}\begin{bmatrix}2.98 & 0.43\\ 550 & 85\end{bmatrix}\begin{bmatrix}\Delta\lambda_{\mathrm{LPG}}\\ \Delta\lambda_{\mathrm{HB-FLM}}\end{bmatrix} \tag{2}$$

with $\Delta\lambda$ in nanometers, ΔT in °C and $\Delta\varepsilon$ in $\mu\varepsilon$ (microstrain).

Fig. 5 shows a real-time experimental demonstration of simultaneous measurement of both physical parameters. The tubular oven was heated at, approximately, 60 °C and gradually cooled down to 20 °C during 20 min. At the same time, a periodic step strain of 200 $\mu\varepsilon$ was applied. The given system output response for simultaneous change of temperature and strain was as expected.

IV. Conclusion

A sensing head based on a combination of an LPG and an HB-FLM was described. With this setup, it was possible to demonstrate that simultaneous temperature and strain measurement could be achieved. The maximum errors for temperature and strain measurements were found to be ±0.8 °C and ±21 $\mu\varepsilon$, respectively. The error uncertainty was measured and is approximately half the maximum error values obtained by the matrix method. This uncertainty is limited by the maximum resolution of the OSA.

This configuration setup allows different kinds of multiparameter measurements that can be made by tailoring the LPG characteristics. Some examples are, for instance, temperature with bending, pressure, or refractive index measurements and others.

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