Discrimination of Temperature, Strain, and Transverse Load by Using Fiber Bragg Gratings in a Twisted Configuration

S. F. O. Silva, O. Frazão, J. L. Santos, F. M. Araújo, and L. A. Ferreira

***Abstract*—A sensing head based on two fiber Bragg gratings arranged in a twisted configuration is proposed to measure three parameters simultaneously, namely 1) temperature, 2) strain, and 3) transverse load. One of the gratings is impressed into a high-birefringence fiber that provides two distinct spectral signatures, which, together with the signature of the second grating and the geometric characteristics of the sensing head, enable the degrees of freedom required to achieve the simultaneous measurement functionality. The resolutions achieved with this configuration for the measurement of temperature, strain, and transverse load are $\pm 3.1\ ^{\circ}$C, $\pm 46\ \mu\varepsilon$, and ± 0.01 N/mm, respectively.**

***Index Terms*—Discrimination of physical parameters, gratings, optical fiber sensors.**

I. Introduction

FIBER Bragg gratings (FBGs) are devices with impressive sensing characteristics, which are essentially grounded to the fact that measurand information is encoded in their resonance wavelengths, which are an absolute parameter and therefore bring the properties of immunity to optical power fluctuations, with no need for recalibration procedures and natural identification of a particular sensor in a series-multiplexed sensing array. Similar to what happens with most sensing elements, when FBGs are applied to the detection of measurands other than temperature, their cross sensitivity to this parameter is an issue that needs to be taken into account. One common approach to solve this limitation is to design sensing heads that are insensitive to temperature. An alternative approach is the conception of structures with enough degrees of freedom to permit simultaneous discrimination of different measurands. This path has been worked out by many researchers, and a significant number of configurations exhibiting this discrimination functionality have been proposed [1].

Due to their practical importance, solutions oriented to the simultaneous measurements of the pair strain and temperature have been particularly researched. As a result, configurations with different levels of performance were demonstrated and applied in field demanding situations. However, there are cases where the measurement of transverse load is needed in addition to the measurement of strain and temperature. The solutions previously proposed are not easily expandable to fulfil this requirement.

The simple measurement of transverse load has been demonstrated using different sensing-head concepts, e.g., Bragg gratings written in high birefringence (Hi-Bi) fibers [2], long period gratings (LPGs) whose transmission spectrum splits and shifts due to the induced birefringence caused by the transverse load [3], and a pair of coupled LPGs [4]. Examples of configurations that were proposed for simultaneous measurements of more than two parameters are given as follows: the use of dual overlaid FBGs written in a Hi-Bi fiber to measure the temperature and three components of strain in composite materials [5]; the combination of an FBG and a Fabry–Pérot interferometer for simultaneous measurements of strain, temperature, and vibration [6]; the utilization of a superstructure fiber grating whose narrowband spectral peaks have different sensitivities to temperature and strain and broadband peak splits due to the induced birefringence caused by transverse load [7]; the implementation of a miniaturized sensing head based on three FBGs written in three fibers located along an equilateral triangle geometry for the simultaneous measurements of curvature, plane of curvature, and temperature [8]; and the consideration of a sampled FBG for simultaneous measurements of strain, temperature, and curvature [9]. In addition, Abe *et al.* [10] proposed a structure based on FBGs that are superimposed in the same position as an internal elliptical cladding (IEC) Hi-Bi fiber to simultaneously measure strain, transverse strain, and temperature.

Recently, we reported the development of a fiber twisted configuration with two FBGs written in a single-mode optical fiber for simultaneous measurements of strain and temperature [11]. In this paper, this concept is further explored to permit additional measurement of transverse load by replacing one of the standard fibers by a Hi-Bi fiber.

II. Theory

The principle behind the sensing-head concepts that permit simultaneous measurements of a number of parameters N is the identification of N characteristics of the sensing-head structure, which change differently under the action of the measurands under concern. In the particular but important case of linear dependences, it is always possible to write N independent

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equations that allow explicit solutions for the actual value of each measurand to be obtained, even in the situation where all of them are changing. In the present case, the measurands are strain, temperature, and transverse load. The sensing structure is based on a twisted configuration where one FBG is kept straight and the other one is twisted with a constant period. The straight FBG is written in a single-mode optical fiber, and the twisted one is impressed in a Hi-Bi fiber. Since the Hi-Bi fiber has different propagation constants for the slow and fast polarization axes, the FBG written in this fiber has two distinct resonance wavelengths, corresponding to each of those axes. It is the different dependences of these three Bragg wavelengths on strain, temperature, and transverse load that make the simultaneous measurements of these physical parameters possible.

The Bragg-wavelength dependences on temperature T, strain ε, and transverse load L can be written as

$$\Delta\lambda_i = K_{\mathrm{T}i}\Delta T + K_{\varepsilon i}\Delta\varepsilon + K_{Li}\Delta L, \qquad i = 1, \mathrm{fast}, \mathrm{slow} \tag{1}$$

where $\Delta\lambda_1$ is the wavelength shift for the grating written in the single-mode fiber and $\Delta\lambda_{\mathrm{fast}}$ and $\Delta\lambda_{\mathrm{slow}}$ are the wavelength shifts for the polarization resonances of the grating written in the Hi-Bi fiber. The quantities $K_{\mathrm{T}i} = \partial\lambda_i/\partial T$, $K_{\varepsilon i} = \partial\lambda_i/\partial T$, and $K_{Li} = \partial\lambda_i/\partial T$ are the temperature-, strain-, and transverse-load-sensitivity coefficients, respectively. Equation (1) can be written in matrix form as follows:

$$\begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_{\mathrm{fast}} \\ \Delta\lambda_{\mathrm{slow}} \end{bmatrix} = \begin{bmatrix} K_{T_1} & K_{\varepsilon_1} & K_{L_1} \\ K_{T_2} & K_{\varepsilon_2} & K_{L_2} \\ K_{T_3} & K_{\varepsilon_3} & K_{L_3} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\varepsilon \\ \Delta L \end{bmatrix} = [\mathbf{K}] \begin{bmatrix} \Delta T \\ \Delta\varepsilon \\ \Delta L \end{bmatrix}. \tag{2}$$

The measurand values can be calculated by inverting (2), which gives (3), shown at the bottom of the next page.

In (3), D is the determinant of the matrix $[\mathbf{K}]$ given by

$$D = K_{T_1}\left(K_{\varepsilon_2}K_{L_3} - K_{\varepsilon_3}K_{L_2}\right) - K_{\varepsilon_1}\left(K_{T_2}K_{L_3} - K_{T_3}K_{L_2}\right) + K_{L_1}\left(K_{T_2}K_{\varepsilon_3} - K_{T_3}K_{\varepsilon_2}\right). \tag{4}$$

In order to have a sensing head with proper discrimination performance, this determinant must have values not too small [12].

III. Experiment

To demonstrate the proposed concept, the sensing-head structure shown in Fig. 1 was implemented. It consists of a straight FBG written in a single-mode fiber (SMF 28) FBG_1 and a twisted FBG written in Hi-Bi fiber (IEC) FBG_2 with a twisting period $\Lambda \approx 10$ mm, which corresponds approximately to the FBG length. Both gratings were written with UV exposure through a phase mask by using an excimer laser operating at 248 nm. In the fabrication process, two uniform phase masks were used, leading to gratings with different Bragg wavelengths. The inscribed gratings had resonance peaks localized around $\lambda_1 = 1558.0$ nm for FBG_1 and $\lambda_{\mathrm{fast}} = 1565.7$ nm and $\lambda_{\mathrm{slow}} = 1566.2$ nm for FBG_2. To prevent the gratings from breaking during the twist process, they were both recoated using Desolite 950-200. An erbium-doped broadband source was used to illuminate the sensing head through a standard 3-dB coupler. The spectral shifts of the FBGs resonances were measured using an optical spectrum analyzer.

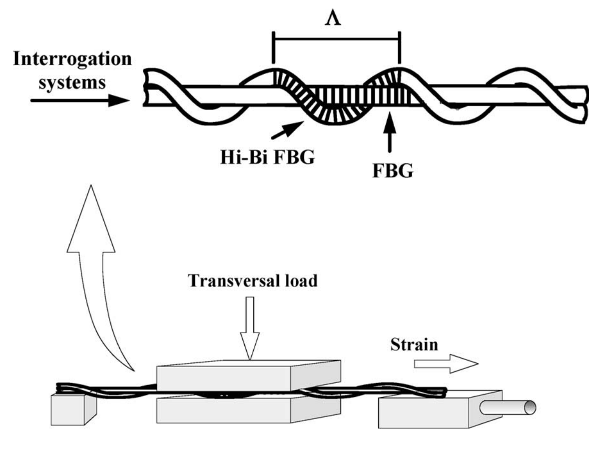

Fig. 1. Sensing-head architecture.

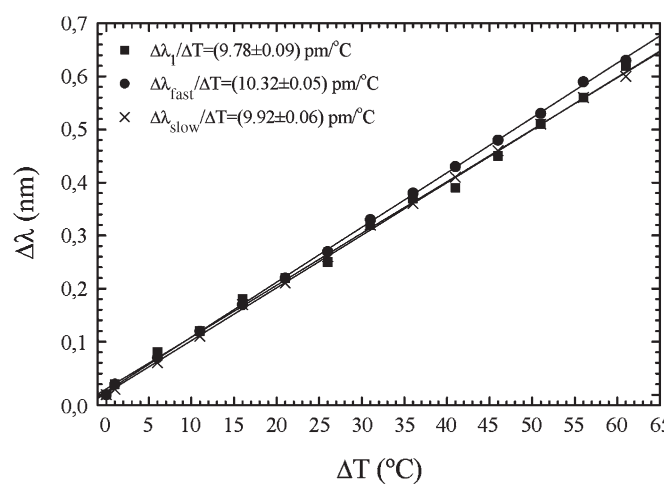

Fig. 2. Bragg-wavelength shifts versus temperature.

To calibrate the sensing structure, independent variations of temperature, strain, and transverse load were sequentially applied. In what concerns temperature characterization, the sensing head was placed in a tube furnace and submitted to increasing values of temperature at constant strain and transverse load. The corresponding results are shown in Fig. 2. As expected, the Bragg resonances have linear responses to variation of temperature, with similar sensitivities: $\Delta\lambda_1/\Delta T = 9.78 \pm 0.09$ pm/°C, $\Delta\lambda_{\mathrm{fast}}/\Delta T = 10.32 \pm 0.05$ pm/°C, and $\Delta\lambda_{\mathrm{slow}}/\Delta T = 9.92 \pm 0.06$ pm/°C. Because the wavelength shifts are mainly due to refraction-index variations, there is only a slight difference between the thermal coefficients of the Bragg wavelengths corresponding to the two polarization states in the Hi-Bi fiber. It would be obviously advantageous to have a larger difference for these coefficients. Processes to achieve this will be considered.

To measure the Bragg-wavelength dependences on strain, the sensing head was fixed at two points and submitted to specific strain values by using a translation stage. The measurements

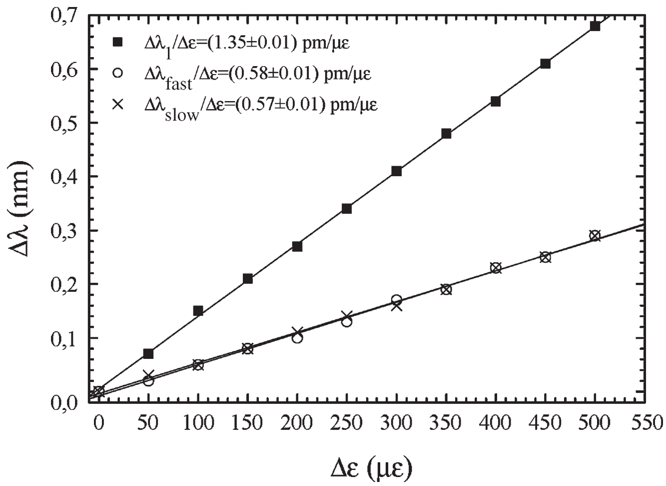

Fig. 3. Bragg-wavelength shifts versus strain.

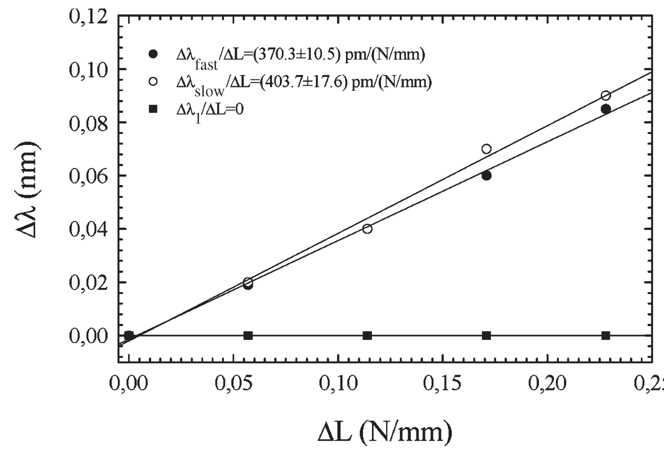

Fig. 4. Bragg-wavelength shifts versus transverse load.

were performed at constant temperature (room temperature) and with zero transverse load. Fig. 3 shows the obtained results.

The obtained strain sensitivity for FBG_1 (straight grating) is $\Delta\lambda_1/\Delta\varepsilon = 1.35 \pm 0.01$ pm$/\mu\varepsilon$. Smaller values for the strain sensitivity of the gratings in the Hi-Bi fiber should be expected because the twist of this fiber converts some of the applied strain into radial strain, which has a significantly smaller effect on the Bragg wavelengths [1]. The experimentally obtained results confirm this effect: $\Delta\lambda_{\text{fast}}/\Delta\varepsilon = 0.58 \pm 0.01$ pm$/\mu\varepsilon$ and $\Delta\lambda_{\text{slow}}/\Delta\varepsilon = 0.57 \pm 0.01$ pm$/\mu\varepsilon$. Actually, these values can be tuned to a certain extent by adjusting the twisting period Λ [11], which is a favorable feature of this configuration in view of the optimization of its measurand discrimination performance.

To characterize the effect of transverse load on the Bragg grating signatures, the sensing head was sandwiched between two horizontal plates, and different weights were placed on top of them. A second set of twisted fibers was placed parallel to the gratings arrangement in order to prevent the upper plate from tilting while the load was being applied. The measurements were performed at constant temperature (room temperature) and constant strain. Fig. 4 shows the change in the Bragg wavelength of each grating as a function of transverse load, which is defined has $force\ applied/2\ell$, with ℓ being the length of the upper plate.

The straight grating FBG_1 shows no sensitivity to the applied load, which was an expectable result. The same does not happen for the two grating signatures from the Hi-Bi fiber: $\Delta\lambda_{\text{fast}}/\Delta L = 370.3 \pm 10.5$ pm/(N/mm) and $\Delta\lambda_{\text{slow}}/\Delta L = 403.7 \pm 17.6$ pm/(N/mm). Again, these values may be adjusted in a limited range by modifying the twisting period.

With the sensitivities quoted previously for temperature, strain, and transverse load, (3) becomes

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \\ \Delta L \end{bmatrix} = -\frac{1}{439.22} \begin{bmatrix} 23.04 & -544.97 & 499.94 \\ -492.31 & 3947.99 & -3621.83 \\ 0.13 & 7.82 & -8.26 \end{bmatrix} \times \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_{\text{fast}} \\ \Delta\lambda_{\text{slow}} \end{bmatrix}. \quad (5)$$

To assess the system performance, one measurand was changed, while the other two were set to constant values. The quantities $\Delta\lambda_1$, $\Delta\lambda_{\text{fast}}$ and $\Delta\lambda_{\text{slow}}$ were measured and inserted into (5) to obtain the calculated values of ΔT, $\Delta\varepsilon$, and ΔL, which were then compared with the real ones. This operation was repeated for the two other measurands. Fig. 5 shows the obtained results. The spread of the calculated data from the actual measurand values indicates a system resolution of ± 3.1 °C, ± 46 $\mu\varepsilon$, and ± 0.01 N/mm for the temperature, strain, and transverse load, respectively. These values can be improved, in principle, by tuning the individual sensitivity coefficients of the sensing head to variations of temperature, strain, and transverse load, within a certain range. The most critical case concerns the sensitivity of the sensing head to temperature, which is similar for the three Bragg grating signatures. Therefore, it would be advantageous to have a larger difference between the thermal coefficients of these signatures in order to optimize the discrimination performance of the sensing head. This may be achieved by considering the Bragg gratings written in optical fibers with different doping characteristics. For example, it was demonstrated that fiber Bragg gratings in B/Ge-codoped fiber

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \\ \Delta L \end{bmatrix} = \frac{1}{D} \begin{bmatrix} K_{\varepsilon_2}K_{L_3} - K_{\varepsilon_3}K_{L_2} & K_{\varepsilon_3}K_{L_1} - K_{\varepsilon_1}K_{L_3} & K_{\varepsilon_1}K_{L_2} - K_{\varepsilon_2}K_{L_1} \\ K_{T_3}K_{L_2} - K_{T_2}K_{L_3} & K_{T_1}K_{L_3} - K_{T_3}K_{L_1} & K_{T_2}K_{L_1} - K_{T_1}K_{L_2} \\ K_{T_2}K_{\varepsilon_3} - K_{T_3}K_{\varepsilon_2} & K_{T_3}K_{\varepsilon_1} - K_{T_1}K_{\varepsilon_3} & K_{T_1}K_{\varepsilon_2} - K_{T_2}K_{\varepsilon_1} \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_{\text{fast}} \\ \Delta\lambda_{\text{slow}} \end{bmatrix} \quad (3)$$

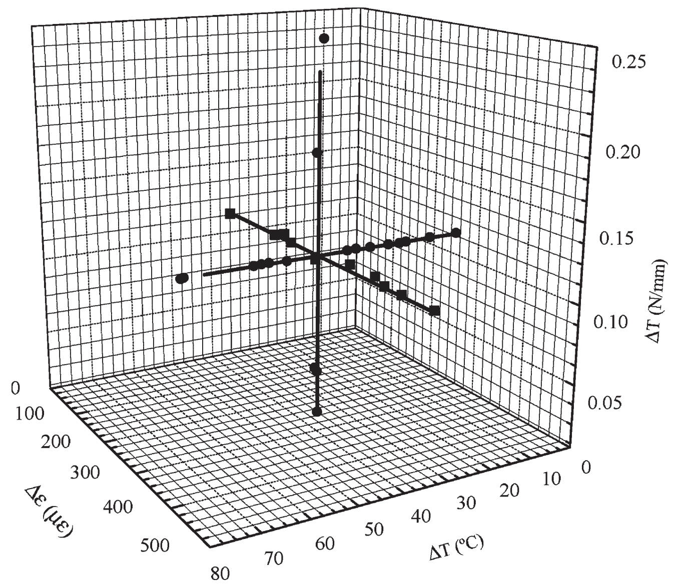

Fig. 5. Sensor output as obtained from (5) when one measurand was changed and the other two were kept at constant values (repeated for all the measurands).

exhibit strong dependence of temperature sensitivity on grating type, thus revealing a difference of 36% between type IA and type IIA temperature coefficients [13]. This means that if the straight fiber were of the IIA type, the corresponding grating would have a substantially different temperature coefficient relative to the gratings impressed in the Hi-Bi fiber, improving significantly the measurand resolution values obtained. Another possibility could be the utilization of a Hi-Bi fiber with a larger difference in its thermal coefficients relative to standard fiber, as is the case of the PANDA Hi-Bi fiber [14].

In what concerns the sensing-head coefficients to strain and transverse load, some tuning can be achieved through modification of the twisting period. However, it is understood that for the same noise level in the measurement system, the resolution achievable for each measurand degrades when the number of parameters for simultaneous discrimination increases. This is due to error propagation through the discrimination matrix and can be observed by comparing the present case with the situation where only the simultaneous measurements of strain and temperature are under concern. Nevertheless, the reported performance is still adequate for many practical cases where simultaneous measurements of temperature, strain, and transverse load are required.

IV. Conclusion

A fiber-optic sensing head projected for simultaneous measurements of temperature, strain, and transverse load has been presented and described. It is based on two FBGs in a twisted arrangement, where one FBG is written in a monomode fiber, and the other one is written in a Hi-Bi fiber. The performance of the sensing configuration was theoretically analyzed and experimentally evaluated. The proposed multiparameter-sensing concept proved to be effective, with the measurement resolutions sufficient for a number of applications. In addition, a few factors that can contribute to further optimization of the sensing-head performance were also identified.

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