

Simultaneous Measurement of Strain and Temperature Using Bragg Gratings Written in Germanosilicate and Boron-Codoped Germanosilicate Fibers

P. M. Cavaleiro, F. M. Araújo, L. A. Ferreira, J. L. Santos, and F. Farahi

Abstract—A new fiber Bragg grating sensor configuration is presented for simultaneous measurement of strain and temperature. The sensor utilizes the effect of boron codoping on the temperature dependence of the refractive index in germanosilicate fibers. By writing gratings with close wavelengths in undoped and boron doped fibers, different temperature sensitivities are obtained while strain sensitivities remain the same. These gratings are then spliced to obtain a simple sensor head suitable for applications in smart structures and composite materials.

Index Terms—Embedded sensors, fiber Bragg gratings, fiber optic sensors, simultaneous measurement.

I. INTRODUCTION

IN RECENT YEARS, a considerable number of techniques for temperature and strain discrimination based on fiber Bragg grating (FBG) sensors have been proposed and demonstrated [1]. In principle, simple schemes that rely only on the use of FBG's in the sensor head are more attractive to be integrated in smart structures and composite materials. In fact, sensor heads based on the combination of gratings with different types of sensors (Fabry-Pérot [2], long period grating [3], rocking filter [4]) often involve a high degree of complexity in both fabrication and interrogation processes. In a letter by Xu *et al.* [5], a fiber sensor was presented using two superimposed fiber Bragg gratings written at different wavelengths in order to obtain distinct temperature sensitivities. However, since the thermo-optic coefficient has a small dependence on wavelength, high separation between the Bragg wavelengths is required for effective temperature/strain discrimination. An alternative approach based on Bragg gratings with close wavelengths written in different diameter fibers was later proposed by James *et al.* [6]. In this case, different strain coefficients

were obtained when axial stress was applied to the sensor. However, when such a sensor is embedded in a structure, its young modulus is determined primarily by the surrounding material and therefore the strain sensitivity of the two segments becomes almost similar. Also, splicing between dissimilar fibers leads to high insertion losses and a reduction of the sensor mechanical strength. Another sensor design exploits the different temperature dependence of the two reflection peaks observed when a Bragg grating is inscribed in PANDA or bow-tie fibers [7], [8]. These sensors have, in fact, appropriate characteristics for integration in composite materials, but the complexity of the required interrogation scheme can limit their applicability. Some disadvantages related to the previous reported techniques for temperature/strain discrimination can be overcome by using a Bragg grating simultaneously sensitive to temperature and strain and an additional strain-immune grating as a temperature reference [9], [10]. However, in order to implement this technique, proper mechanical protection of the reference grating is needed, which can lead to practical constraints in the process of embedding the sensor.

In this letter, we report on a new sensor design suitable for simultaneous measurement of strain and temperature in smart structures and composite materials. The sensor has two gratings with close wavelengths written in two spliced sections of germanosilicate fibers with identical geometry, one of them is codoped with boron. In this way, a small sensing element with two Bragg gratings of similar strain sensitivities but different responses to temperature can be constructed.

II. THEORY

Fig. 1 shows in detail the geometry of the proposed sensor head. Temperature and strain variations applied to the gratings cause shift in their Bragg wavelengths as

$$\Delta\lambda_{Bi} = K_{Ti}\Delta T + K_{\epsilon i}\Delta\epsilon \quad (1)$$

where $i = 1, 2$ represent the grating written in the germanosilicate fiber and in the boron-codoped-germanosilicate fiber, respectively. The thermal sensitivity, K_{Ti} , depends on the thermal expansion of the fiber and, essentially, on the thermo-optic coefficient. On the other hand, the strain sensitivity, $K_{\epsilon i}$, depends on the photoelastic coefficient of the fiber, but is mainly determined by the variation of the grating pitch

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P. M. Cavaleiro, F. M. Araújo, and L. A. Ferreira are with Unidade de Optoelectrónica e Sistemas Electrónicos, INESC PORTO, 4169-007 Porto, Portugal.

J. L. Santos is with the Departamento de Física da Universidade do Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal and Unidade de Optoelectrónica e Sistemas Electrónicos, INESC PORTO, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal.

F. Farahi is with the Physics Department, University of North Carolina at Charlotte, Charlotte, NC 28223 USA.

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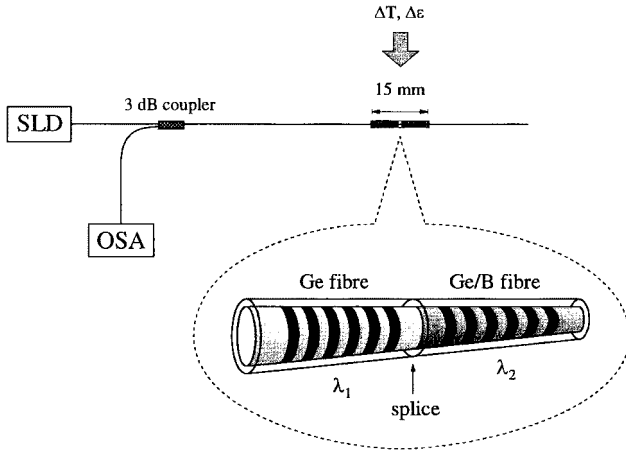


Fig. 1. Experimental setup and sensor head geometry.

with the applied strain, which depends on the mechanical properties of the fiber. It is well known that the presence of boron in the core of optical fiber leads not only to a decrease of the refractive index but also to a decrease in thermo-optic coefficient [11]–[13]. Hence, it is expected that the temperature dependence of the Bragg wavelength can be modified by boron codoping of germanosilicate fiber. Considering the fact that boron codoping has no observable effect on the mechanical properties of the fiber, we conclude that, in general, $K_{T1} \neq K_{T2}$ and $K_{\epsilon 1} = K_{\epsilon 2}$. In this way, (1) can be used to discriminate between temperature and strain effects applied to the sensor head:

$$\begin{bmatrix} \Delta T \\ \Delta \epsilon \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} K_{\epsilon 2} & -K_{\epsilon 1} \\ -K_{T2} & K_{T1} \end{bmatrix} \begin{bmatrix} \Delta \lambda_{B1} \\ \Delta \lambda_{B2} \end{bmatrix} \quad (2)$$

where $\Delta = K_{T1}K_{\epsilon 2} - K_{\epsilon 1}K_{T2}$. Clearly, the efficiency of the method depends on the difference between K_{T1} and K_{T2} , which is determined by the concentration of boron in the codoped germanosilicate fiber.

III. EXPERIMENT AND DISCUSSION

The FBG's used in these experiments were fabricated using the following fibers: Siacor SMF1528, simple germanosilicate core, 6 mol% of GeO_2 , cold-hydrogenated at 100 atm; Fibercore PS1500, boron-germanosilicate-codoped core, 10 mol% of GeO_2 and 14–18 mol% of B_2O_3 (value estimated from fiber numerical aperture and data available in literature). For practical convenience and for the propose of experimental demonstration, different phase masks were utilized in the grating fabrication process, leading to gratings with $\lambda_{B1} \approx 1300$ nm, $\lambda_{B2} \approx 1280$ nm, and more than 95% reflectivity. The gratings were thermally annealed and spliced close to each other, resulting in a sensor head with total length $L < 15$ mm. This short length ensures single-mode operation of the grating in the boron codoped fiber, although its cut-off wavelength is 1402 nm. Since the geometry and numerical aperture of the two fibers are identical, a standard low loss splice could be achieved (insertion loss < 0.02 dB). This sensor head was then placed in a temperature-controlled chamber where it could be simultaneously subjected to axial strain variations. As shown in Fig. 1, the gratings were illuminated with a

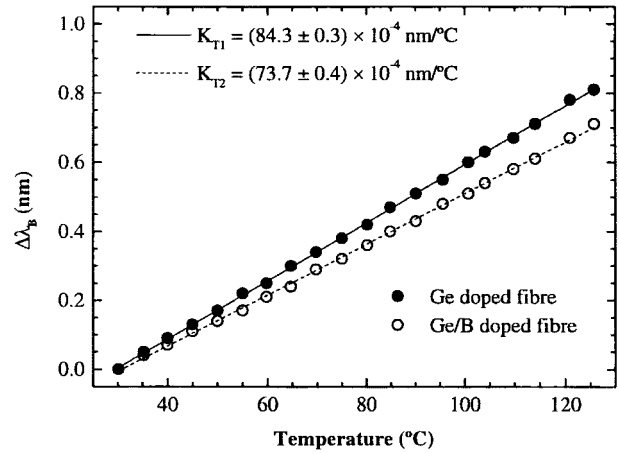


Fig. 2. Sensor response to temperature.

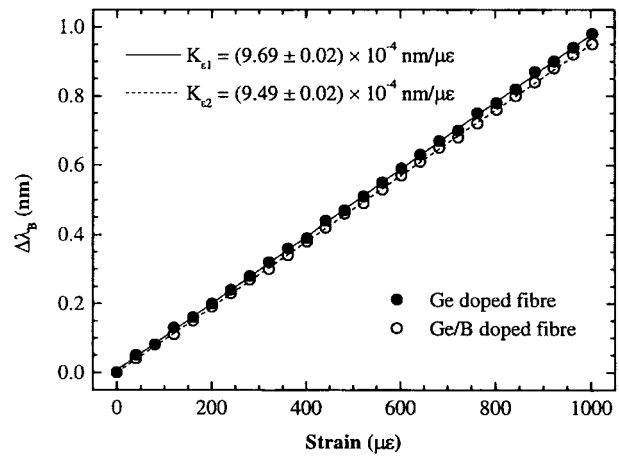


Fig. 3. Sensor response to applied strain.

superluminescent diode source ($\lambda_o = 1280$ nm), and an optical spectrum analyzer was used to measure the induced central wavelength shifts of the reflected peaks.

Figs. 2 and 3 show the responses of the two sensing gratings to applied temperature and strain variations, respectively. As expected, different temperature sensitivities are observed for the two gratings, but they exhibit similar response to applied strain. We must emphasise that the small difference between $K_{\epsilon 1}$ and $K_{\epsilon 2}$ results only from different operating wavelengths rather than from material characteristics. Substitution of the obtained coefficients in (2) yields

$$\begin{bmatrix} \Delta T \\ \Delta \epsilon \end{bmatrix} = 116.5 \begin{bmatrix} 9.49 & -9.69 \\ -73.7 & 84.3 \end{bmatrix} \begin{bmatrix} \Delta \lambda_{B1} \\ \Delta \lambda_{B2} \end{bmatrix}. \quad (3)$$

Equation (3) and data from the optical spectrum analyzer output were used to predict strain and temperature simultaneously applied to the sensor head. In the measurement range of 100°C and 1 $\mu\epsilon$, the maximum experimental errors obtained were within ± 2.2 $^\circ\text{C}$ and ± 18.4 $\mu\epsilon$, essentially determined by the resolution of the optical spectrum analyzer. In principle, better resolution can be achieved if more sensitive fiber Bragg grating interrogation schemes are utilized [14]. Toward this goal, Bragg gratings written in germanosilicate fibers with

higher levels of boron codoping must also be considered, as well as fibers with different codopants.

The measurement range in the proposed sensing scheme is only limited by possible cross-sensitivity problems [15], since fusion splice between similar fibers does not compromise the fiber intrinsic mechanical strength [16]. In addition, the obtained low-loss splice, together with the wavelength-encoded characteristic of the sensor head, makes this system very attractive for wavelength multiplexed sensing networks. On the other hand, the small size, simplicity, and low fabrication complexity of this sensor are important characteristics for embedded sensors in composite materials. It is of particular importance to note that the strain/temperature discrimination is based on difference in thermal sensitivities of the sensing gratings. This allows suitable protection coatings and sensor demodulation schemes to be chosen based on the application requirements and with no regard to the sensor design.

IV. CONCLUSION

We have designed and fabricated a fiber sensor that consists of two Bragg gratings written in germanosilicate-core and boron-codoped-germanosilicate-core fibers. Due to boron codoping, different temperature sensitivities and similar response to strain were obtained. These properties have been used to simultaneously measure strain and temperature applied to the sensor.

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