Strain and Temperature Transducer on one Fiber Bragg Grating

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ABSTRACT

Strain and temperature measurement using one Fiber Bragg Grating transducer is demonstrated. The device is constructed in a hydrogenated standard telecommunication optic fiber with one-step optimized UV writing process. A complete strain and temperature characterization is reported to asses the viability of this device.

Keywords: Temperature-Strain Discrimination, Fiber Bragg Gratings, Second Order Diffraction

1. INTRODUCTION

Fiber Bragg Gratings (FBG) are one the most interesting devices to build up of fiber optic transducers debt to its small size joined with the typical advantages of fiber optic as are electromagnetic interference immunity, low weight, etc. The profitable ability of this device for the measurement of several important physic magnitudes such as strain and temperature allow a new range of applications reserved previously to classical measurement techniques. Some complex problems arise when practical sensors are designed owing to the comparable sensibilities of FBG to both physic magnitudes. Appropriate design strategies must be adopted to provide simultaneous measurement of both strain and temperature[1].

In some specific applications, making use of special geometric characteristics of the structure to be measured, a convenient placement of the FBG transducers can give a temperature independent measurement[2]. However, for making a more nonspecific transducer, a hard engineering problem must be faced. Several successful schemes have been developed to discriminate between strain and temperature[3]. The most simple and intuitive method to achieve this purpose consists on the design of a transducer head formed with two FBGs written at different wavelengths and mounted with one of them isolated from strain[4]. The generalization of this idea have permitted the design and construction of rosettes very similar to the classical strain gages[5]. However, the increased transducer size and a expensive waste of optical bandwidth are the main drawbacks of this approach. Compact designs and smart bandwidth usage can be made with the writing of two superimposed FBGs[6]. Although both FBGs are affected by the two physical parameters, their initial Bragg wavelengths can be chosen to lay far enough one from the other in order to avoid an ill-conditioned transfer matrix. The main drawback or this idea is that a two-step writing process can complicate the construction of the device. This negative aspect can be overcome with a design based on the writing of a single FBG in the fiber with a one-step writing. A unique and optimized writing process to the optic fiber can produce FBGs with not only the first Bragg wavelength peak but also a second order diffraction peak offering two Bragg wavelength measurements able to provide the discrimination between temperature and strain.

As a general rule, in order to obtain simultaneous measurement of temperature (T) and strain (ε) the design strategy to be used is based on the obtention of two observable parameters (ϕ_1 and ϕ_2). The transfer matrix that describes the transduction mechanism is :

$$\begin{bmatrix} \Delta\phi_1 \\ \Delta\phi_2 \end{bmatrix} = \begin{bmatrix} K_{1T} & K_{1\varepsilon} \\ K_{2T} & K_{2\varepsilon} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} \quad (1)$$

where K_{1T} and $K_{2\varepsilon}$ are the temperature and strain sensitivities whilst K_{2T} and $K_{1\varepsilon}$ and the undesirable cross-sensitivities[7]. To recover the desired information, first of all the matrix inversion must be possible and afterwards the final performance of the technique depends on the resultant condition number of the matrix.

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As a result of the technique proposed, two observable parameters (ϕ_1, ϕ_2) are measured which are first and second order diffraction Bragg wavelengths. The primary wavelength measurement is a relatively easy task and there's not a problem to achieve a high reflectivity for obtaining a good measurement of the Bragg wavelength. However, secondary wavelength reflectivity hasn't been studied enough. Second order diffraction efficiency from FBG written within germanosilicate optical fibers was first reported by Xie et al[8]. However, the use of hydrogenated standard telecommunication fibers for the FBG writing offers the possibility of a cost-effective method for mass producing this type transducers and the use of this technique for simultaneous measurement of strain and temperature was proposed by Brady et al[9]. Here, in this work, in first place, a hydrogenated optical fiber saturation index change characterization was made. Second, using this information, a simulated an experimentally tested optimized UV-writing process have been designed. This process maximizes first and second order diffraction wavelengths peak detection. In third place, several FBGs were constructed with this optimized writing process and after an appropriate annealing they were thoughtfully characterized. Its ability to be used as a strain and temperature transducer and some interesting conclusions are obtained.

2. TRANSDUCER DESIGN AND FABRICATION PROCESS

Standard telecommunication optic fibers have small photosensitivity but hydrogen loading make them capable to be used for FBG fabrication. The fiber core refraction index is incremented by the UV-writing process in a predefined pattern. This process is assumed to be quasi-linear under low UV exposition energies. In practice, this behavior is only linear until a saturation index change value is reached. In this case, although the refraction index of the non-saturated areas of the fiber core is still increased with the UV exposition, the refraction index of the saturated areas is increased no more. As consequence, the resultant index profile had a non-sinusoidal axial shape as is shown in figure 1. A low exposition energy like E_1 produces a linear increment in all the fiber optic core, but higher exposition energies as E_2 produces a different profile with a higher second order diffraction wavelength peak.

The index increment versus the UV exposition for a standard hydrogenated telecommunication optical fiber was experimentally obtained[10]. While the fiber was exposed to the UV light , a Mach-Zehnder fibre interferometer with the fiber as one of its arms was used to monitorize the index refraction change. A behaviour model was developed with this information and several simulations of the index profiles for different FBG lengths and exposition energies was made and tested experimentally.

A design example of the evolution of the reflectivities of first and second order diffraction peaks in function of the exposition energy and for two different FBG lengths is depicted in figure 2. The optimum energy zone marks the exposition energy which balances the both peak reflectivities. The exposition energy that balances both diffraction peak amplitudes is independent from the length of the FBG. Phase mask method was used to inscribe the FBGs and the influence of the '0'-order diffraction mode was analysed and simulated[10]. A very small linear degradation was observed concluding that this effect is negligible.

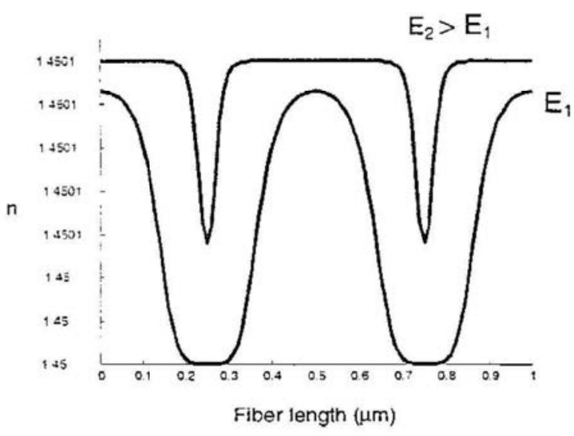

Fig. 1. Phase mask fabrication resultant axial index profiles on the optic fiber for two different exposition energies E_1 and $E_2 > E_1$.

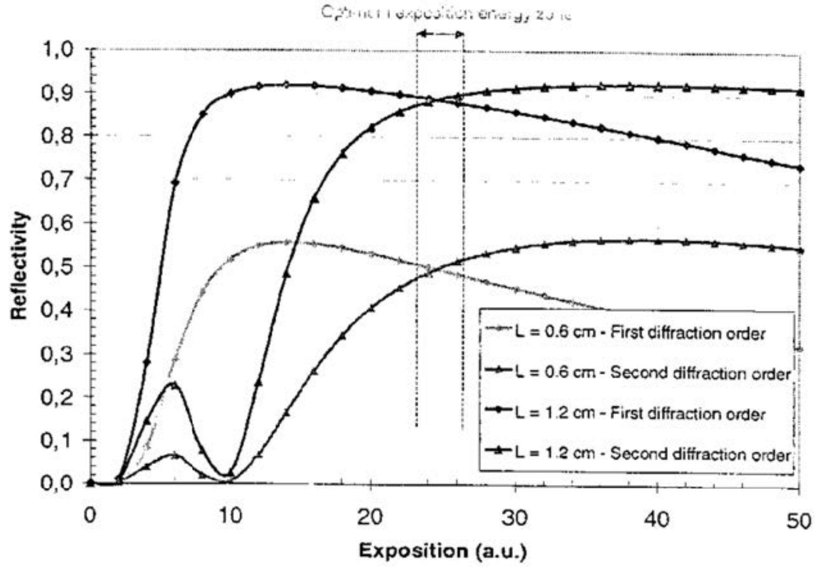

Fig. 2.Evolution of the reflectivity of the first and second order diffraction wavelengths vs. the exposition energy for Fiber Bragg Gratings of lengths L = 0.6 cm and L = 1.2 cm. The optimum exposition energy zone is delimited.

3. EXPERIMENTAL CHARACTERIZATION

A high resolution (1pm) spectrum characterization spectrum was made to each FBG at 25°C using a wavelength meter and a tunable laser in a closed loop configuration to achieve the desired wavelength repetitivity. The data obtained was used later for increasing the wavelengths displacement measurement precision. The resultant FBG devices showed the first peak wavelength at 1536.85 nm and a second peak wavelength at 767.94 nm with good peak reflectivities. A experimental setup, which is depicted in figure 3, was designed to achieve a complete characterization of the devices. The setup consists on two broadband light sources, each one with maximum light power at the wavelengths of interest, two optical switches to increase the flexibility and repetitivity of the measurements and an optical spectrum analyzer for obtaining transmission and reflection spectrums. All the setup is computer controlled to automatize the measurements.

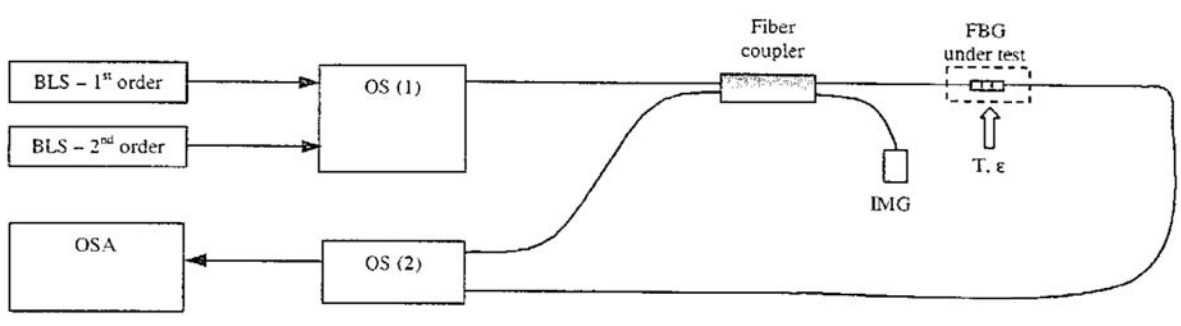

Fig. 3.Experimental computer controlled setup used for the characterization. BLS : Broadband Light Source, OSA: Optical Spectrum Analyzer, OS : Optical Switch, IMG: Index Matching Gel.

3.1. Temperature characterization results

Each FBG was inserted in a climatic chamber. The temperature of the chamber was swept in 5°C steps from 0°C to 100 °C. Waiting for the temperature stabilization in each state a sufficient number of transmission and reflection measurement were acquired for first and second order diffraction wavelengths. A photograph with the laboratory setup for these measurements is shown in figure 9.. Several reflection spectrums obtained at different temperatures for first and second order diffraction wavelengths is shown in figure 4. Transmission spectrums showed similar behavior and joined to reflection spectrums, temperature calibration functions were obtained for first and second order diffraction wavelengths. These results as well as the linear regression lines are shown in figure 5. A high degree of linearity for this temperature range and a close relation between spectrums obtained from both sides of the FBG are observed.

One possible cause of measurement errors is the fact that at second order diffraction wavelengths standard telecommunication fibers are multimodal. However, in the acquired data, no appreciable interference from higher order modes was observed. In order to test this possibility a numerically normalized correlation calculus between first and second order spectrums were made showing a high degree of similarity validating the above mentioned affirmation.

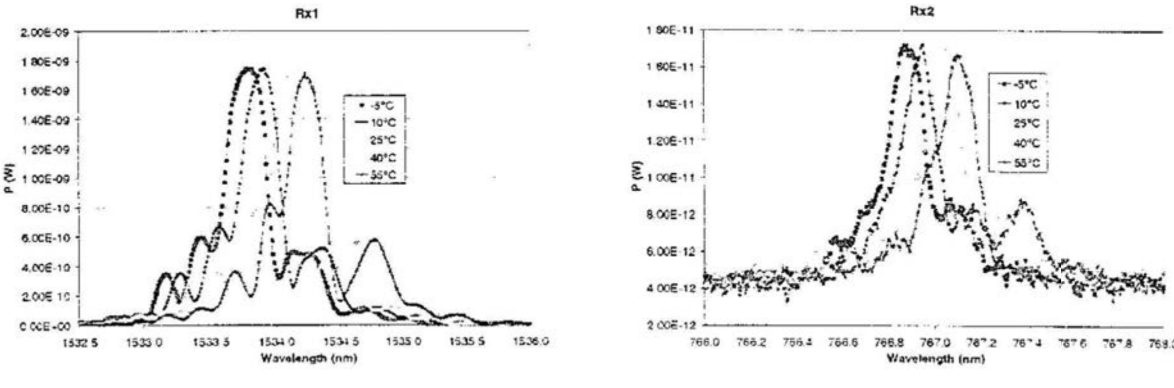

Fig. 4.Reflection spectrums obtained at first (Rx1) and second (Rx2) order diffraction wavelengths for different temperatures.

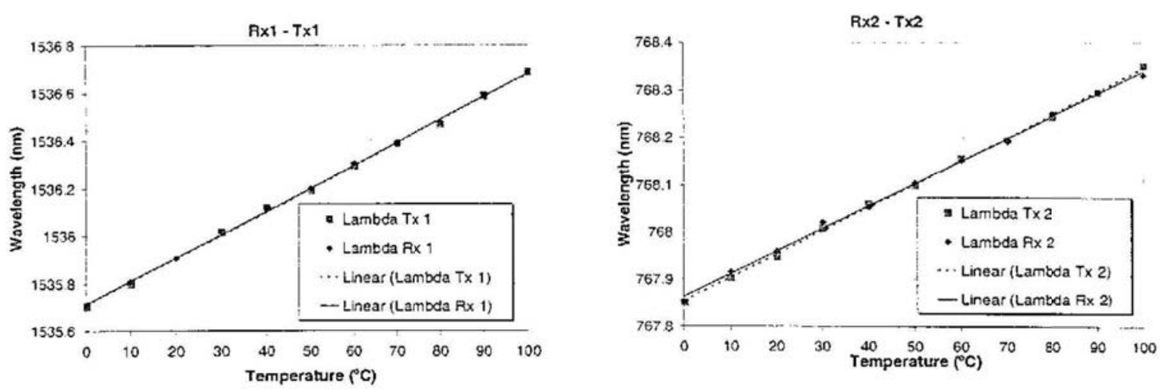

Fig. 5.Temperature calibration functions obtained at first order diffraction wavelengths from reflection (Rx1) and transmission (Tx1) spectrums, and at second order diffraction wavelengths from reflection (Rx2) and transmission (Tx2) spectrums.

3.2. Strain characterization results

The strain characterization of the FBGs was achieved making use of a computer controlled precise displacement device. A certain length of the fiber containing the FBG was glued to the displacement stage. The distance between optical fiber glued points was measured to obtain the strain applied to the fiber as a relation between this distance and the minimum repeatable displacement obtained with the displacement device. As a result of this calculus, calibrated displacements a fixed 25 °C temperature from 0 με to 1800 με in 100 με steps were made. The corresponding transmission and reflection spectrums at both first and second order diffraction wavelengths were recorded. Several samples of the acquired data are shown in Fig. 6. Calibrations functions at both wavelengths were obtained from the acquired data which are shown in figure 7.

As it was made for temperature, an analysis comparing reflection and transmission spectrums at both wavelengths was made to detect any possible interference of additional modes at low wavelengths. Results showed the same conclusions obtained before.

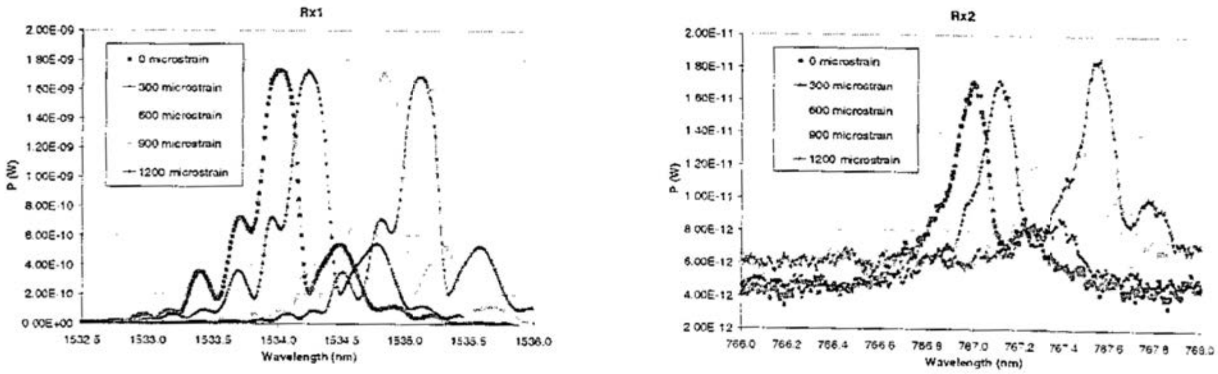

Fig. 6.Reflection spectrums obtained at first (Rx1) and second (Rx2) order diffraction wavelengths for different strain conditions.

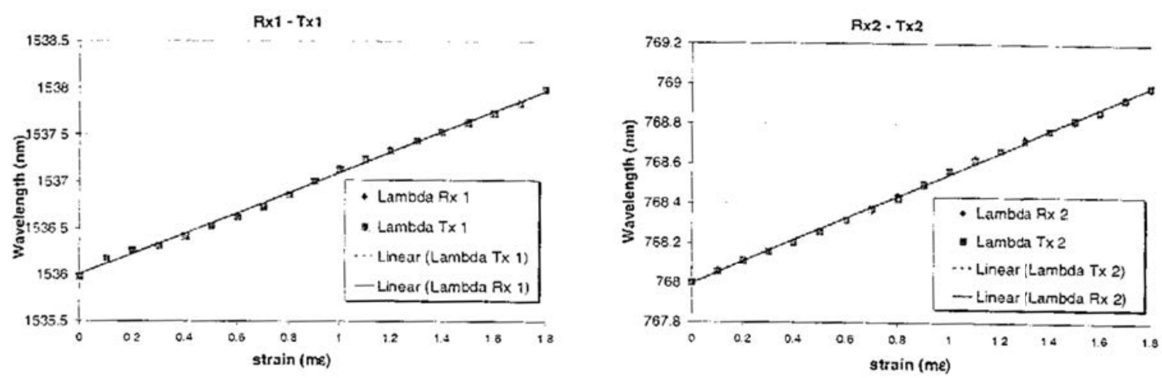

Fig. 7. Strain calibration functions obtained at first order diffraction wavelengths from reflection (Rx1) and transmission (Tx1) spectrums, and at second order diffraction wavelengths from reflection (Rx2) and transmission (Tx2) spectrums

3.3. Simultaneous temperature and strain characterization

In order to prove the independence between both measurands, strain and temperature, of the response of these devices, a simultaneous strain and temperatures characterization was made. Each fiber containing the FBG was glued to a calibrated motion device which was calibrated for straining the fiber. The length of the optic fiber between glued points was metered and a again a strain relation was obtained. The part of the fiber containing the FBG was covered with a heat chamber and its temperature was controlled with a thermoelectric cooler connected with a precision temperature sensor (0.1°C). The temperature of the chamber was swept in 15°C steps from −5° to 55 in 15°C steps combined with a strain sweep from 0 $\mu\varepsilon$ to 1200 $\mu\varepsilon$ in 300 $\mu\varepsilon$ steps to achieve a mapping of the response of the devices. In this characterization the optic setup depicted in figure 3 was used, too. The transmission and reflection profiles acquired was processed as explained before and results at both wavelengths are depicted in figure 8. In this figure the different linear slopes for temperature and strain can be observed it showed that are independent one from the other.

According to the experimental results, the transfer matrix coefficients of this device are:

$k_{1T} = 9.70 \pm 0.03$ pm/°C $\quad k_{1\varepsilon} = 1.092 \pm 0.013$ pm/$\mu\varepsilon$

$k_{2T} = 4.89 \pm 0.02$ pm/°C $\quad k_{2\varepsilon} = 0.472 \pm 0.006$ pm/$\mu\varepsilon$

Supposing that transfer matrix coefficients are measured with enough precision, the errors associated to the measurement of strain and temperature are limited by the resolution in the measurement of the primary and secondary Bragg wavelengths. These errors also depends on the specific values of the coefficients and if it's assumed than the wavelength metering device has 1 pm wavelength error in the measurement at both wavelengths, error analysis of the resultant matrix[9] give strain and temperature errors better than those already reported.

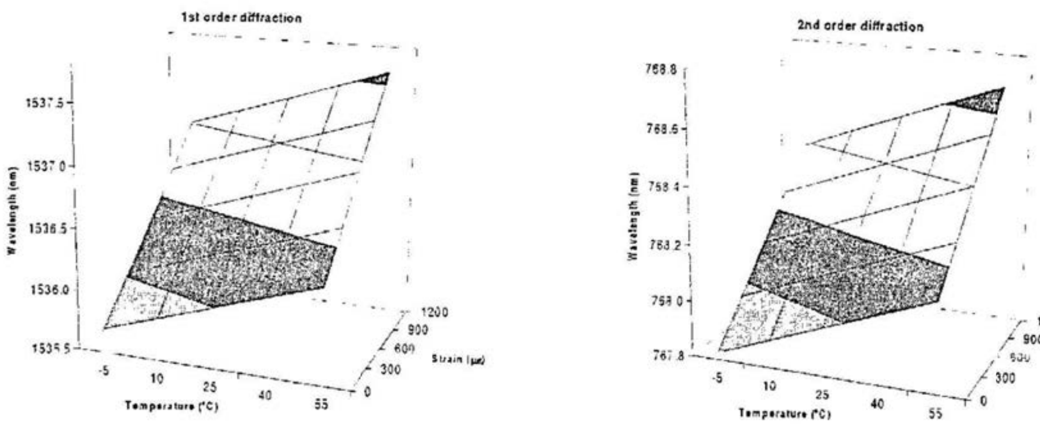

Fig. 8.Simultaneous strain and temperature calibration functions for 1st and 2nd order diffraction wavelengths obtained from reflection and transmission spectrums.

4. CONCLUSIONS

The strain and temperature experimental characterization of the above referred single uniform FBGs, written with a optimum UV exposition energy has been made. Experimental spectrum response from both sides was obtained in order to achieve a complete characterization of the devices. The temperature and strain first and second order diffraction wavelength calibration functions show good linearity in the response of the devices. No interference in the measurements at second order diffraction wavelengths derived from multimodal behavior of the standard telecommunication at lower wavelength was observed. The results obtained suggest the feasibility of this single FBG based transducer in order todiscriminate strain and temperature.

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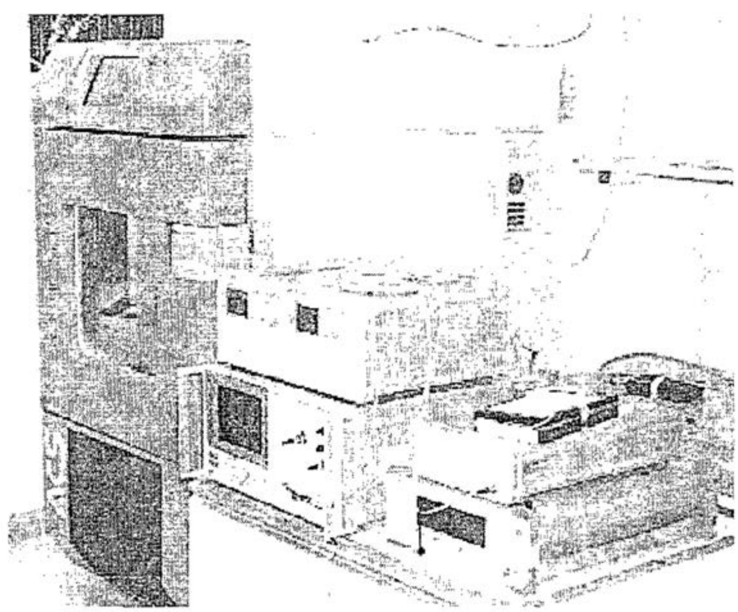

Fig. 9.Photograph of the experimental setup used for temperature characterization.