FIBER BRAGG GRATING SENSORS: NEW IDEAS ON STRAIN-TEMPERATURE DISCRIMINATION

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Abstract- - In this paper, two novel methods are discussed, wherein Fiber Bragg Gratings are used as sensors to discriminate strain and temperature, simultaneously. These methods provide a good linear response and involve simple fabrication & implementation of the sensors.

Index terms: Fiber Bragg grating sensors, strain sensor, temperature sensor, strain and temperature discrimination.

I. INTRODUCTION

After the phenomenal discovery by Hill et al [1], Fiber Bragg Gratings (FBGs) have attracted considerable interest, due to their applications in a variety of fields including telecommunication, and sensing. FBGs have brought out a revolution in the area of sensors as they offer several advantages over conventional electrical or mechanical sensors. The most important advantages are

(a) FBG sensors are rugged passive components resulting in a high lifetime (~20years).

(b) FBGs can form an intrinsic part of the fiber optic cable that can transmit the measured signal over several tens of kilometers.

(c) FBGs show no interference with the electromagnetic radiation and can function in many hostile environments where conventional sensors would fail.

(d) The absence of electrical signals render FBGs explosion safe.

FBGs are also proved to be superior candidates in comparison with other fiber optic sensing elements, due to the ease of multiplexing into arrays and hence providing a distributed sensing capability. Though FBGs have proved to be efficient devices in strain and temperature sensing, the discrimination between these two parameters remains as one of the key challenges in their practical deployment. The measurement of the perturbation induced wavelength shift from a grating does not facilitate the discrimination of the sensor's response to these two measurands. This has serious implications for strain sensors designed to measure quasi-static signals, as any temperature variation along the fiber will be indistinguishable from strain. However, this is not an issue for dynamic strain measurements, as the thermal fluctuations occur at low frequencies that tend not to coincide with the resonance frequencies of interest.

Temperature compensating methods can be classified into two categories, namely extrinsic (combining the grating with an external material of suitable properties and dimensions) or intrinsic (relying on the fiber properties) methods. In extrinsic methods, the compensation of temperature sometimes is not exact and hence intrinsic methods have become more popular. In intrinsic methods, using two sensors with one isolated from either of the unwanted perturbations, could be the simplest approach; however, the use of a second sensor may not be practicable in applications where sensors must be embedded with minimal intrusion. Efforts are going on to implement a single element sensor where the strain and temperature can be encoded into information other than wavelength shift. Regardless of the exact details, any scheme should ideally be compatible with a large number of gratings to facilitate multiplexing. Table I gives a list of the current existing and demonstrated methodologies for strain/temperature discrimination.

This paper highlights two new interesting ideas for discerning strain from temperature effects using FBG sensors. The focus has been to introduce new intrinsic techniques towards simplicity in implementation of the sensor; these are the dual characteristic wavelength shift method and single element method.

The first method is based on the measurement of the different characteristic wavelength shifts of two types of gratings. Strain and temperature sensitivities of a Type I Bragg grating (G_1) in germania doped silica fiber, fabricated under normal conditions, and zero strain, are compared with that of a Bragg grating inscribed under pre-strained condition (G_2). Experimental results show that both, strain and temperature sensitivities of G_1 and that of G_2 are different. Based on this study, an approach has been proposed which enables simultaneous discrimination of axial strain and temperature.

In the second method, a single sensing element has been used to encode strain and temperature into an additional parameter other than the wavelength shift. The thermal out-diffusion of germanium from the core of a photosensitive fiber at elevated temperatures is exploited to form a

Fabry-Perot filter within a single FBG. The filter is fabricated using the standard phase-mask technique and one-time exposure. Energy Dispersive X-Ray analysis is used to measure the out-diffusion. The filter is used as a sensor for simultaneous measurement and discrimination of strain and temperature.

Table 6.1: Summary of performance of strain and temperature separating schemes for FBGs [2]

Compensating Method	**Strain**	**Temperature**	**Extrinsic/ Intrinsic**
Two Bragg gratings mounted on opposite surfaces of a cantilever	$1\mu\varepsilon$/pm	Not measured	Extrinsic
Passive temperature compensating package	$70\mu\varepsilon$/pm on 120°C range	Not measured	Extrinsic
Dual-wavelength superimposed gratings	$17\mu\varepsilon$/pm	1.7K/pm	Intrinsic
Multiple Bragg grating orders	$17\mu\varepsilon$/pm	1.7K/pm	Intrinsic
Panda fiber gratings	$20\mu\varepsilon$/pm	2°C	Intrinsic
Gratings in dissimilar diameter fibers	$17\mu\varepsilon$/pm	1K/pm	Intrinsic
Hybrid/LPG	$9\mu\varepsilon$/pm	1.5°C	Intrinsic
Bragg grating strain rosettes	$3\mu\varepsilon$/pm + $2.5\mu\varepsilon$	0.14K/pm	Intrinsic
Dual-core FBG	unknown	unknown	Intrinsic
Fibers with different polymer coating	unknown	unknown	Intrinsic
Type I and Type IIA FBGs	$8.49\mu\varepsilon$	1.5°C	Intrinsic
FBG cavity sensor	$30\mu\varepsilon$	0.4°C	Intrinsic
Tapered grating	unknown	unknown	Intrinsic

The organization of the paper as follows. Section II and III describe the dual characteristic wavelength shift method and single element method respectively, after a brief introduction to the various strain-temperature discrimination techniques, Section IV gives a brief summary of the presented techniques and the scope for future work.

II. DUAL CHARACTERISTIC WAVELENGTH SHIFT METHOD

Stretching a photosensitive optical fiber modifies the stress distribution frozen within the core and cladding, rendering lesser densification in the glass matrix. This leads to an increase in the kinetics of type IIA refractive index modulation in the pre-strained fiber [3]. The difference in the grating evolution dynamics of unstrained and pre-strained fiber is responsible for the difference observed in temperature sensitivity (τ). An earlier work [4] suggests that the temperature response of FBGs depends on its type, namely I, IA or IIA. An additional difference in the strain sensitivity (ε) is demonstrated in this work. Here, the type IIA grating has been fabricated in a pre-strained fiber under short term exposure (conditions similar to that of Type I grating) unlike that reported in [5], wherein the Type IIA grating is fabricated by prolonged exposure.

a. Sensor fabrication

In the present work, Gratings G_1 and G_2 are inscribed in a 10mol% germania doped fiber (Fibercore, SM1500 :4.2 / 80 / 005). A KrF excimer UV laser at 248nm with a pulse energy of 2.56mJ and a pulse repetition rate of 200Hz has been used to inscribe G_1 using a phase mask with a pitch Λ_{pm} =1069nm. Prior to the inscription of grating G_2 at a distance of 30cm from G_1, the fiber is fixed at one end, clamped to a precision translation stage at the other end and stretched to impart about 3000$\mu\varepsilon$ on the fiber. G_2 is now inscribed using a similar inscription process as that of G_1. After grating inscription, the strain on the fiber is released.

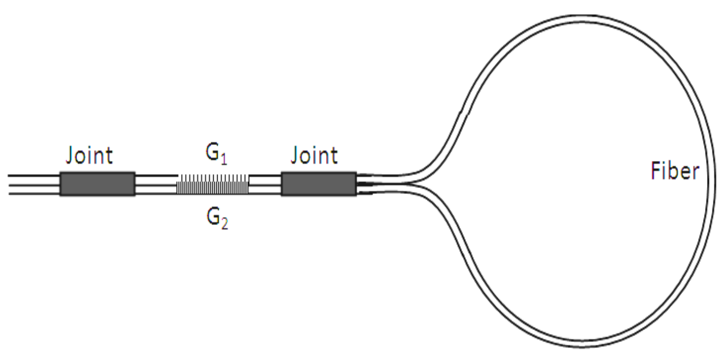

Fig.1: Schematic of the sensor unit showing Type I grating G1 and Type IIA grating G_2 placed adjacent to each other

G_1 and G_2 are positioned as close as possible to each other by looping the fiber as shown in Fig.1. This allows the gratings to experience the same strain and temperature perturbation. The Bragg wavelengths of G_1 and G_2 measured with an optical spectrum analyzer (Anritsu MS9001B1) are 1540.86nm and 1538.38nm, respectively.

b. Experimental results

Strain and temperature sensitivities, ε and τ of G_1 and G_2 are measured by applying strain and temperature individually to the sensor unit. The wavelength shifts are measured using an Optical Spectrum Analyzer (OSA). For obtaining "ε", the sensor unit and a Resistance Strain Gauge (RSG) are bonded on a carbon fiber composite coupon in a cantilever arraignment for a comparative study. Maximum tensile strain of 800με is applied. The thermal response of the sensor unit from 26°C (room temperature) to 120°C is calibrated with a K-type Thermocouple (T/C). The strain and temperature response of the sensor is shown in Fig. 2.

The ε of G_1 and G_2 are found to be 1.20 pm/με and 1.32 pm/με respectively, and the τ of G_1 and G_2 are 11.64 pm/°C and 12.20 pm/°C, respectively. Since, the ratio of the strain responses of the two gratings is different from that of their temperature responses, simultaneous changes in strain and temperature can be discerned independently from the wavelength shifts of G_1 ($\Delta\lambda_{B1}$ an$\Delta\lambda_{B2}$), using the matrix equation (1):

$$\begin{pmatrix} \Delta S \\ \Delta T \end{pmatrix} = \begin{pmatrix} 1.20 & 11.64 \\ 1.32 & 12.20 \end{pmatrix}^{-1} \begin{pmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{pmatrix} \tag{1}$$

The ratio of the strain and temperature responses of G_1 and G_2 is found to be 6%, which competes well with other techniques available in literature [5]. The advantage with the present technique lies in the fact that the ratio can be further enhanced by increasing the pre-strain while inscribing G_2. This technique also fares better, as the kinetics of Type IIA in G_2 has been enhanced only by applying a strain during fabrication, instead of using long exposure of a UV laser with high power.

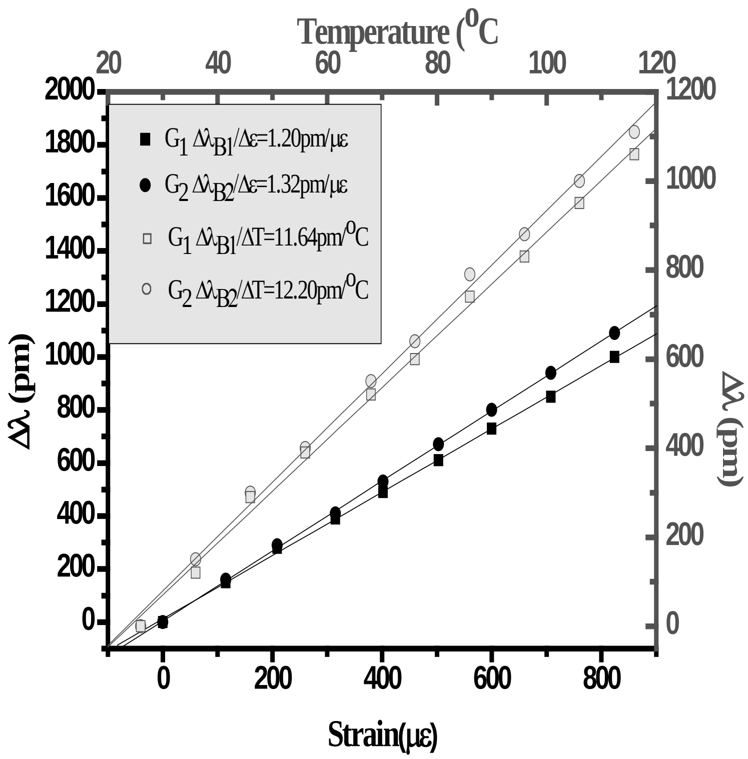

Fig.2: Dependence of Bragg wavelength shifts of G1 and G2 on strain and temperature.

The proposed technique offers a number of advantages such as, small and compact size, easy implementation and above all a linear response which requires only a simple interrogation system. Since there is no special packaging, the sensor unit demonstrated here allows direct access to the gratings.

III. SINGLE ELEMENT METHOD

In this method, the thermal out-diffusion of germanium from the core of a photosensitive fiber under elevated temperature is exploited to form a Fabry-Perot filter with a single fiber Bragg grating. The filter is fabricated using the standard phase-mask technique and one-time exposure. Energy Dispersive X-Ray analysis (EDAX) is used to measure the out-diffusion. The filter is used as a sensor for simultaneous measurement and discrimination of strain and temperature.

a. Sensor fabrication

The fabrication of FP-FBG employs the dopant out-diffusion phenomenon [6] in a localized region of a photosensitive optical fiber produced by a standard fusion splicer. By modifying the concentration of Ge, the strength of the grating can be controlled for a given exposure time and energy of the UV beam. Fig.3 shows the fabrication process, where a photosensitive fiber with

10 mol % Ge (Fibercore (SM1500 (4.2/80)/005)), is cleaved (Fig.3(i)) and spliced (Fig.3(ii)) using a Fujikura fusion splicer (FSM-50S). The fusion temperature during splicing (>1800°C) causes the out-diffusion of the dopant Ge from the core of the fiber, resulting in the reduction of photosensitivity over a length "d". The dopant out-diffusion for a given photosensitive optical fiber depends on the number of arc discharges across the electrodes. In the present study, the number of discharges has been optimized at 5.

Upon one-time UV exposure using 248nm KrF UV laser and phase-mask (Λ_{pm}=1064nm) over a length of L=3mm, (L > d), two gratings are inscribed symmetrically across the thermally-treated region (Fig.3(iii)). Due to the reduced Ge concentration over length d, the strength of the grating is relatively lower. This region effectively acts as the cavity and the two gratings on either side with Bragg wavelength λ_m act as the partially reflecting mirrors of the FP-FBG.

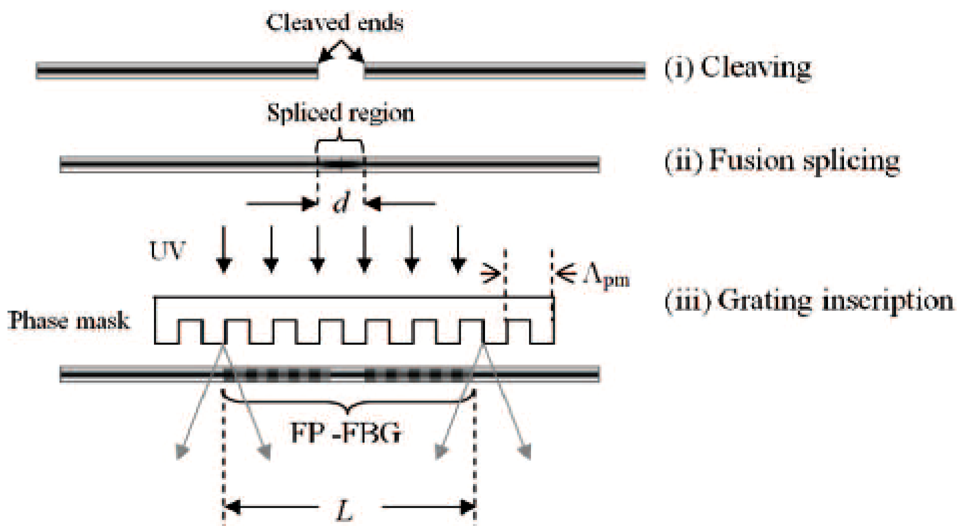

Fig. 3: The fabrication procedure of grating Fabry-Perot filter

b. EDAX results

The wt % distribution of Ge along the fiber diameter before and after the thermal treatment has been examined by Scanning Electron Microscopy (SEM-FEI Sirion-XL40), and Energy Dispersive X-ray analysis (EDAX).

Fig. 4 shows the concentrations (wt %) of Si, O and Ge of regular and thermally altered fibers, respectively. It is evident from Fig.4 that for the thermally treated fiber the wt % is reduced by a factor of 3, with a corresponding increase in the radial spread to ~7.6μm, which clearly indicates the radial out-diffusion of Ge.

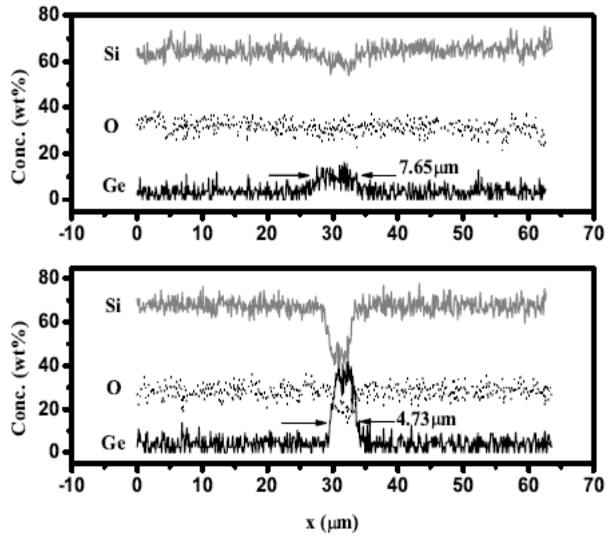

Fig.4: The Si, O and Ge concentration profile of regular fiber (bottom) and spliced fiber (top), taken along the diameter of fiber cross section.

c. Results

In the present method, $dn_c / dT \neq dn_m / dT$, due to the reduced Ge concentration in the cavity spacing. Here, dn_c / dT and dn_m / dT are the thermo-optic coefficients of the cavity and the gratings, respectively. With an increase in temperature, we see that $d\lambda_c/dT < d\lambda_m/dT$. This leads to a periodic power distribution between the two FP peaks, P_1 and P_2, with temperature [7]. However, as the strain-optic coefficients for the cavity and gratings are equal, they will not contribute to the effect.

With a strain of +1400με, measured with an RSG, the grating resonance shifts towards right with no significant change in P_1 and P_2 (Fig.5 (left)). The thermal response of the FP-FBG sensor from 24°C to 95°C has been calibrated with a K-type thermocouple. With an increase in temperature, the sensor wavelength shifts to the right as shown in Fig.5 (right): P_1 and P_2 exhibit a periodic exchange of power (inset in Fig.5(right)).

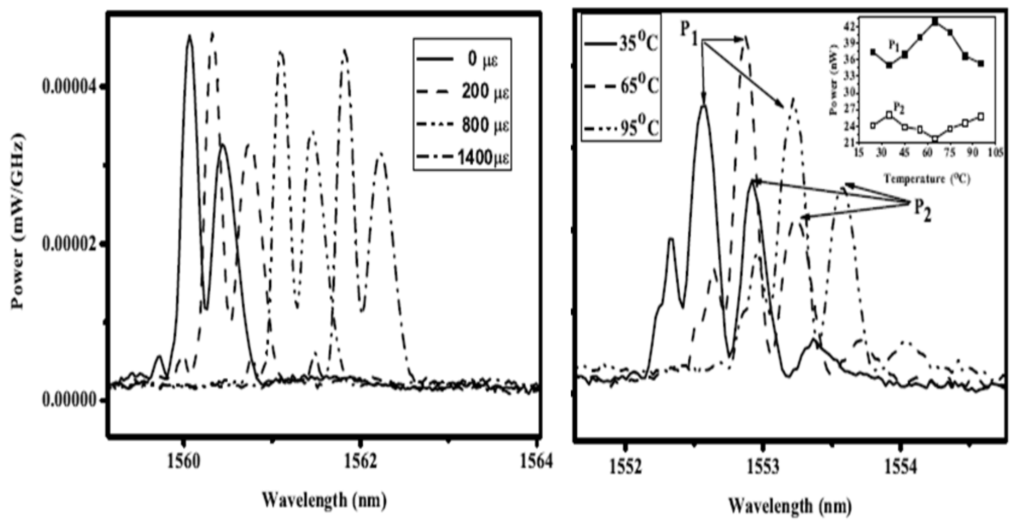

Fig. 5: Reflection spectra with strain (left) and with temperature (right)

The range of measurement depends on the degree of Ge out-diffusion. With an increase in Ge out-diffusion the difference between $d\lambda_c/dT$ and $d\lambda_m/dT$ increases with proportional in the power exchange between P_1 and P_2. In the present case, the temperature measurement range is ~60°C. The advantage of the present sensor lies in the fact that it is a single grating device capable of measurand discrimination.

VI. CONCLUSIONS

The limitations in the deployment of FBG sensors in practical applications come from the fact that FBGs are affected by both strain and temperature fields simultaneously. Implementation of any particular strain/temperature discrimination technique depends on the application environment. For example, an insulated packing used to desensitize the FBG to temperature has been adopted, which is not a viable option where temperature reading needed. Further, the package itself can physically hamper the deployment of the sensor in scenarios such as an embedded system. Each discrimination methodology lies in a landscape of merits and demerits. Based on the application, the right methodology needs to be selected. It is due to this aspect that more novel methodologies have to be continuously developed and added to the growing list. Every new idea for strain-temperature discrimination is an ideal candidate for specific application scenario. In this work, two new schemes have been proposed for the use of Fiber Bragg Gratings as strain-temperature discriminating sensors:

a) The first method is based on the measurement of the different characteristic wavelength shifts of Type I and Type IIA gratings. Experimental results show that their strain and temperature sensitivities different.

b) In the second method, a single sensing element has been used to encode strain and temperature into an additional parameter other than the wavelength shift, by exploiting the thermal out-diffusion of germanium from the core of a photosensitive fiber under elevated temperature, forming a Fabry-Perot filter The filter is used as a sensor for simultaneous measurement and discrimination of strain and temperature. The proposed technique, where a single grating is used to discriminate the parameters, provides a large advantage over other existing methods.

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