FBG 센서의 온도와 변형률 동시 측정기법 기술 분석

Technical review of discrimination method between strain and temperature on the FBG sensor

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ABSTRACT

FBG(Fiber Bragg grating)s have shown a great potential for sensing applications, and are easily embedded in materials with a negligible impact on the mechanical properties of the host. However, the use of FBG sensors is limited by their simultaneous dependence on strain and temperature, thus only one parameter can be determined from a single grating. This paper reviews various methods to discriminate between strain and temperature effects. To overcome this cross sensitivity using only embedded optical fibers, a number of techniques have been proposed, most of them relying on the deconvolution of two simultaneous measurements.

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1. Introduction

Fiber Bragg gratings (FBG) have become a key component for optical fiber telecommunications as wavelength-division multiplexing devices, fiber laser reflectors, gain flattening devices and dispersion compensation element [1], and for sensing applications as temperature, strain, pressure, ultrasound, acceleration, high magnetic field and force, chemical elements [2, 3]. The length of the gratings that can be produced ranges from $100\,\mu m$ to several meters. Long gratings open new perspectives for distributed sensing and dispersion compensation, but in this case the local characterization of the grating parameters is required. FBGs have shown a great potential for sensing applications, and are easily embedded in materials with a negligible impact on the mechanical properties of the host. However, the use of FBG sensors is limited by their simultaneous dependence to strain and temperature. To overcome this cross sensitivity, a number of techniques have been proposed. This paper reviews various methods to discriminate between strain and temperature effects.

2. FBG (Fiber Bragg grating) sensors

In this study of crystals, it is known that X rays are reflected at well-defined directions due to the periodic arrangement of the atoms and these reflections are described by the Bragg equation. In the same way but at larger wavelengths, a periodic refractive index variation in the core of an optical fiber will exhibit specific reflections at the Bragg condition with an angle π (i.e. back-reflection)

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \cdot m \tag{1}$$

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where λ_B is the peak reflection amplitude wavelength, n_{eff} is the effective index of the guided mode, Λ is the grating period (Fig. 1) and m=1,2,3, ... is the Bragg reflection order [4].

For this reason these structures are called fiber Bragg gratings (FBG). FBGs in silica-based optical fiber (with approximate effective refractive index of 1.45) have a grating period between 450 and 500 nm for the lowest Bragg reflection order in the 1300-1500nm range. Higher orders of reflection are possible but not considered here. Fig. 1 shows that a broadband light around the Bragg wavelength launched in the fiber is partly back-reflected with a resonance peak at the Bragg wavelength; the remaining light is instead transmitted.
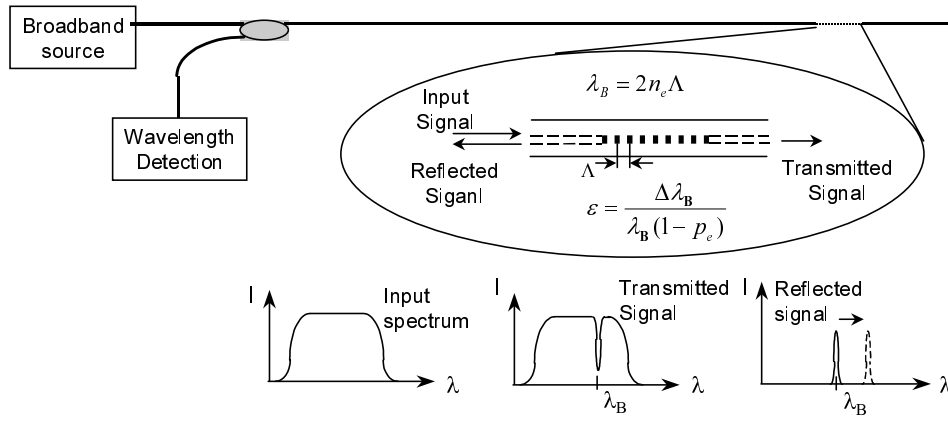

Fig. 1 Fiber Bragg grating and spectral effects.

3. Review of simultaneous measurement methods

3.1 Dual wavelength superimposed FBGs

The spectral behavior of two superimposed fiber gratings having different Bragg wavelength (850, $1300nm$) with respect to strain and temperature was studied [5, 6]. Assuming that the strain- and thermally-induced perturbations are linear, the Bragg wavelength $\Delta\lambda_\varepsilon$ and $\Delta\lambda_T$, in response to a strain change $\Delta\varepsilon$ and temperature change ΔT, can be expressed in the form

$$\Delta\lambda_\varepsilon = K_\varepsilon \Delta\varepsilon$$
$$\Delta\lambda_T = K_T \Delta T \qquad (2)$$

where K_ε is the strain sensitivity and K_T is the temperature sensitivity. K_ε is related to the Poisson ration of the fiber, the photoelastic coefficient, and the effective refractive index of the fiber core and K_T is determined by the thermal expansion coefficient and the thermo-optic coefficient. As the photoelastic and thermo-optic coefficients are wavelength dependent, fractional wavelength changes of each of the two superimposed gratings will be different although each grating is subject to the same level of strain or temperature. In general, the change in Bragg wavelength of the fiber grating $\Delta\lambda_B$, due to a combination of strain and temperature, can be expressed as

$$\Delta\lambda_B(\varepsilon, T) = K_\varepsilon \Delta\varepsilon + K_T \Delta T \tag{3}$$

As a result, for the two wavelengths to be measured, the following equation holds:

$$\begin{pmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{pmatrix} = \begin{pmatrix} K_{\varepsilon 1} & K_{T1} \\ K_{\varepsilon 2} & K_{T2} \end{pmatrix} \begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} \tag{4}$$

where 1 and 2 refer to the two wavelengths respectively. Xu [5] selected 1300 and 850 nm wavelengths taking reasonable strain and thermal response differences. Sivanesan [6] presented a detailed theoretical and experimental analysis of the wavelength selection of dual-wavelength fiber grating sensors as shown in Fig. 2. It is clear from the plots that the system matrix conditioning can be optimized only by careful selection of the temperature coefficients, as the strain coefficients do not vary much in the standard fiber optic wavelength window (0.6 to 1.6 μm). For example, a pair that included 1300 nm and a wavelength between 600 and 800 nm would be a better choice than any other pairs in the wavelength range considered. An enough difference of temperature coefficient, however, is acquired from the large wavelength difference because thermo-optic coefficient has a small dependence on wavelength. It makes measurement system complex and requires two broadband sources.
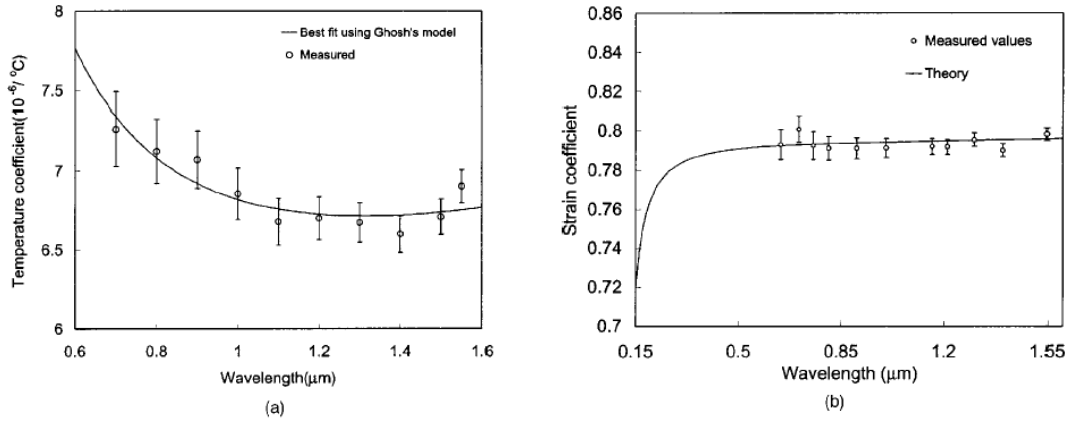

Fig. 2 Experimentally measured temperature and strain coefficients and the best fit using Ghosh's model [6].

3.2 FBGs with spliced different fibers

Fig. 3 shows the structure of the sensor. The grating was written on the splice joint between two different fibers. Because the two fibers have the same diameter, for a given load, a similar variation in the grating pitch would be experienced by the two grating sections.
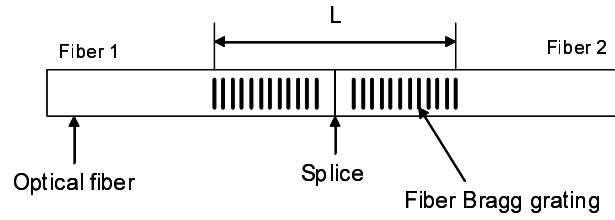
Fig. 3 FBGs with spliced different fibers.

Therefore, it is expected that the two Bragg wavelengths will exhibit similar strain responses. On the other hand, since the composites of the two fibers are different, it is expected that they will possess different thermo-optic coefficients and hence the two Bragg wavelengths would exhibit different temperature responses. To take sufficient difference of the temperature sensitivity, several fiber combinations were studied: Siecor SMF1528 and fibercore PS1500 [7], corning SMF-28 and Er/Yb doped fiber [8], polymer fiber and silica fiber [9].

3.3 Dual diameter FBGs

James in 1996 [10] found that the strain responses to relative wavelength shifts and the temperature responses to the weighted wavelength shift differences of two FBGs with different cladding diameters were not the same, for example, 80 and $125\,\mu m$ as shown in Fig. 4. By fusion-splicing two FBGs with different cladding diameters, two sets of relative wavelength-shift data are obtained for separating strain and temperature. The measured temperature and strain can be, respectively, obtained by equation (4). However, when such a sensor is embedded in a structure, its Yong's modulus is determined primarily by the surrounding material and therefore the strain sensitivity of the two segments becomes almost similar.
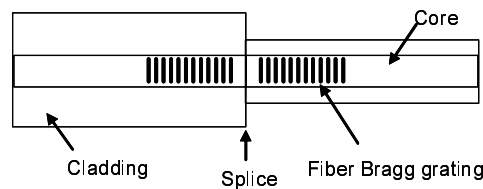

Fig. 4 Dual diameter FBGs.

3.4 Reference FBG method

There are simple and effective techniques using a strain immune grating as a temperature reference. Song [11] reported two closely spaced fiber gratings method embedded is series in a silica glass capillary tube in Fig. 5(a). As both ends of grating were firmly attached to the inner wall of the tube using epoxy, strain-induced elongation is negligible and its Bragg wavelength was not changed by the applied strain. However, in the temperature measurement, its Bragg wavelength change by applied temperature showed nearly the same characteristic. Another similar sensing scheme is shown in Fig. 5(b) [12]. Because one section of the grating was bonded onto the substrate of large thermal expansion coefficient, this section is more difficult to stretch than another section, but its temperature coefficient becomes larger because the expansion of the substrate with temperature causes a change in the grating period. However, in order to implement

this technique, proper mechanical protection of the reference grating is needed, which can lead to practical constrains in the process of embedding the sensor.

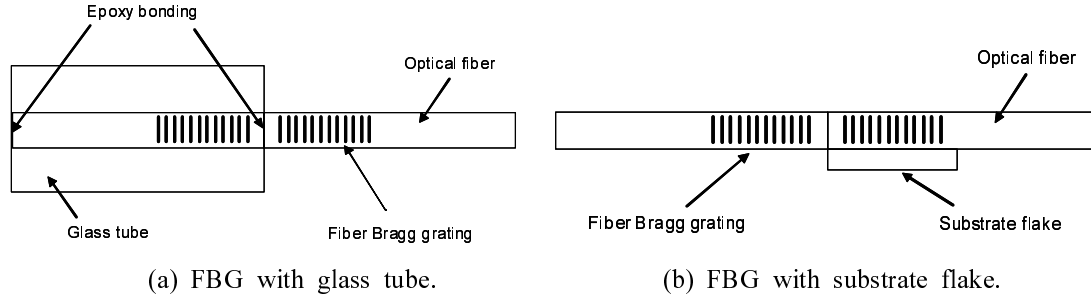(a) FBG with glass tube. (b) FBG with substrate flake.

Fig. 5 Reference FBGs.

3.5 FBGs superimposed with polarization rocking filter

This technique makes use of two different types of photo-induced fiber grating, i.e., a Bragg grating and a polarization-rocking filter [13]. The method relies on the different dependencies of the fiber relative index and birefringence on strain and temperature. To make efficient polarization-rocking filter, elliptical core D-type fiber was used. The broad coupling bandwidth of locking filter ($14\,nm$) made it difficult to measure accurately small shifts of the resonant wavelength for this type of grating. As a solution to this problem, a pair of rocking filters was written on the same piece of fiber. However, long gauge length ($51\,cm$) makes it difficult to use practically.

3.6 FBGs with different grating types

Temperature sensitivity of the Bragg grating depends on the grating type, including the well-known type I, type IIA (inscribed in hydrogen free fiber), type IA (inscribed in hydrogenated fiber) and transformation from one type to another occurred with long UV exposures as shown in Fig. 6.

The grating temperature coefficient is larger in hydrogen-free fiber than in hydrogenated fiber, with type IIA gratings exhibiting the largest value overall and a abnormal grating type, type IA, which occurs in hydrogenated fiber, the lowest value. New configurations with type IA and type IIA grating [14], type I and IIA grating [15] were reported. However, sufficient mechanical strength of FBG is not proved due to the long time UV exposure.

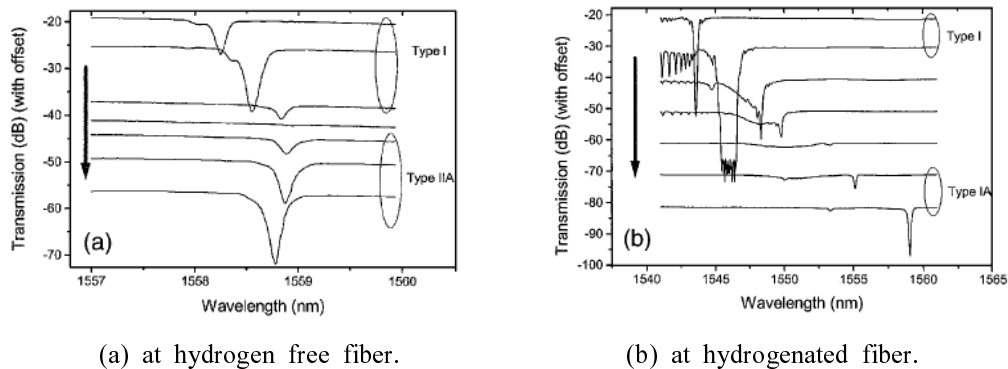(a) at hydrogen free fiber. (b) at hydrogenated fiber.

Fig. 6 Evolution of the transmission spectrum of a grating [14].

3.7 Uniform FBG sensor

Controlling the UV energy during the FBG writing process, the resulting axial index profile in the core of the fiber can be modified from a sinusoidal function to a new nonsinusoidal function. It can even be erased due to the saturation effect of the index change. Due to the nonsinusoidal axial index profile in the fiber core, a first- and second-order diffraction wavelength can be detected. Echevarria [16] reported that the temperature and strain sensitivities depend on the diffraction order. However, the resulting primary and secondary wavelengths had wide wavelength range such as 1536nm and 768nm.

3.8 FBG inscribed in polarization-maintaining fiber

For typical temperature ranges, a considerable difference in thermal sensitivities is expected for FBGs corresponding to the fiber fast and slow axes. However, strain sensitivities must be similar, since in this case the wavelength shifts result mainly from changes in the grating spatial period. Sufficient different coefficient ratios were obtained and strain and temperature were measured simultaneously [17]. However, interrogation scheme to acquire the signal is complex due to the polarization.

3.9 Hybrid EFPI/FBG sensor

Proposed sensing structure is shown in Fig. 7. FBG is encapsulated in a silica capillary tube to be isolated from the external strain. The EFPI cavity was formed between two cleaved fiber ends inserted into the capillary tube. The FBG is in strain-free condition and is only affected by the temperature change within the capillary tube, while the EFPI is affected by both thermal and mechanical strains. Using similar reference FBG method, it was possible to discriminate between strain and temperature and several papers about this sensing scheme [18, 19, 20] were reported. However, it has some constraints about multiplexing and embedding condition due to the glass tube.
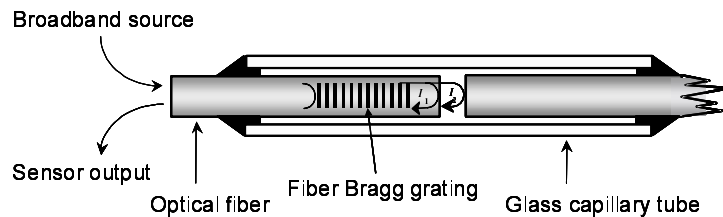

Fig. 7 FBG/EFPI hybrid sensor [20].

3.10 FBG and active doped fiber

The sensor design is based on the combination of fiber grating and active doped optical fiber. The amplified spontaneous emission power of some gain media has a monotonically decreasing dependency on temperature in the range of measurement and varies almost linearly with temperature within a considerable range. Temperature characteristics of erbium-doped fiber [21], erbium:ytterbium-doped fiber [22] and Er/Yb co-doped fiber [23] were reported. By subtracting the temperature effect from the Bragg wavelength shift, strain was determined. As

seen in Fig. 8, however, a long length of active fiber has to be used to enhance the responsibility, which is not a practical solution for quasi-distributed measurement. Fernandez-Valdivielso [24] used thermochromic material as a temperature reference at the end of fiber, but intensity based sensing scheme had a defects about noise essentially.
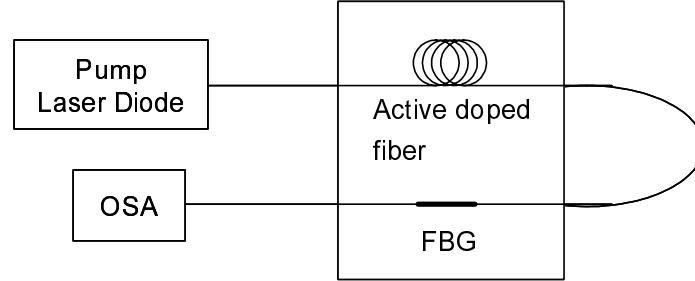

Fig. 8 Experimental setup for FBG and active doped fiber.

3.11 long-period grating

The effects of temperature and strain on the spectra of the first and second-order diffraction attenuation bands of a single long-period grating (LPG) was studied [25, 26]. Strain and temperature responses of the first and second-order diffraction attenuation bands had highly linearity and sufficient separation. Due to the wide attenuation band, however, it needs complex signal interrogation to monitor all cladding modes in each attenuation band.

3.12 Hybrid FBG/LPG sensor

The FBG and LPG responses are different because while the FBG wavelength is linearly proportional to the grating period multiplied by the effective index of refraction of the core, the LPG wavelength is proportional to the grating period multiplied by the difference in index of refraction between the core and the cladding. The strain and temperature response of an FBG depends on the change in the grating period and the change in index of refraction of the core. The response of an LPG depends on the change in the grating period and on the differential change in the core and cladding indexes of refraction. To overcome of the difficulty to measure the center wavelength of the LPG due to the large bandwidth, resonant peak of the LPG was placed between the FBGs [27, 28, 29, 30]. Wavelength shifts of the LPG affect the reflection peak intensity of the FBGs. However, the interrogation of FBGs with LPGs is difficult since the technique requires the resonant peak of FBGs to be located at the band edge of the resonant peak of LPGs and there is a limited sensing range.

4. Conclusion

Methods to discriminate strain and temperature effects include the dual-wavelength superimposed gratings, the use of first- and second-order diffraction grating wavelengths, FBGs in optical fibers with different dopants, hybrid Bragg grating/long period gratings, dual-diameter FBGs, FBGs combined with EDFAs, FBG/EFPI combined sensors, FBGs in high-birefringence optical fibers, the employment of strain-free FBGs and a combination of FBGs of different 'type'. The use of a strain-free reference grating turns out to be the most efficient way to discriminate strain and temperature. On the other hand, it is not easy to implement this technique when

sensors must be embedded into a host composite, since it requires placing one of the gratings within a small capillary tube. As shown above, a number of publications present ideas on the discrimination between the strain and temperature effects, however lots of researches to solve this problem still has been accompanied on the application point [31].

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