Temperature Independent Strain Measurement with a Fiber Grating Tapered Cavity Sensor

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***Abstract*— A novel fiber grating tapered cavity sensor used for encoding strain into its spectral profile independently and its experimental demonstration are presented. The sensor possesses two spectral peaks within its main reflection band and the normalized power difference between the two peaks changes linearly with applied strain while it is independent of temperature variation. The accuracy of this particular sensor in measuring strain is estimated to be ±29 $\mu\varepsilon$ in a range of 1200 $\mu\varepsilon$.**

***Index Terms*— Fabry–Perot (FP) cavity, fiber Bragg grating, temperature independent strain measurement.**

FIBER Bragg grating (FBG) sensors are small and, hence, suitable to be embedded in or attached on some structures for internal/surface strain measurements [1]. One critical limitation of the sensors is that they are sensitive to both strain and temperature simultaneously, which leads to difficulty in the independent measurements for these two measurands. A number of techniques have been reported to overcome this limitation, such as the reference FBG method [2], dual-wavelength FBG's method [3], FBG combined with long-period grating method [4], FBG superimposed with polarization-rocking filter method [5], and dual-diameter FBG method [6]. However, most of them are based on the measurement of two characteristic wavelength shifts related to two different types of gratings. It is highly desirable to measure parameters other than the wavelength shift, such as the power or spectral profile of light reflected from one single FBG sensor, which can be used to encode the change in strain or temperature independently. However, the spectral profile of a conventional FBG sensor usually remains unchanged, though the whole spectrum shifts due to the variation in strain or temperature.

In this letter, we will report a spectral-profile-encoding scheme for temperature independent strain measurement based on a novel all-fiber grating structure, i.e., fiber grating tapered cavity (FGTC) sensor. The sensor possesses two spectral peaks within its main reflection band and the normalized power difference (M) between the two spectral peaks changes linearly with strain while it is independent to temperature. Therefore, the strain can be determined directly by measuring the change in M, and then the temperature is also determined by measuring the peak wavelength shift.

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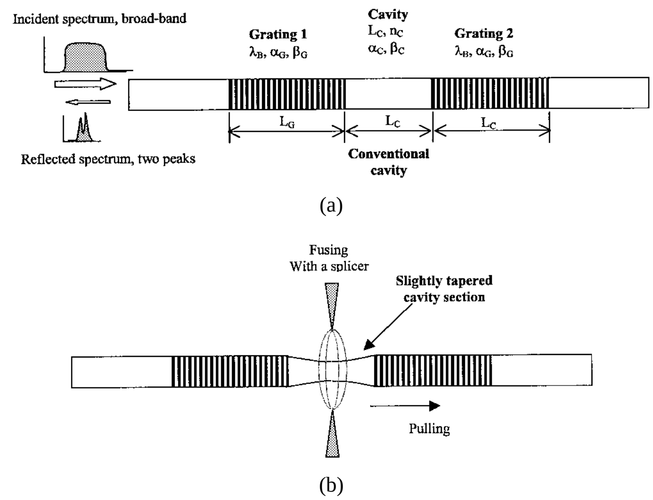

Fig. 1. Structures of a fiber grating cavity comprising (a) conventional cavity and (b) slightly tapered cavity.

Fig. 1(a) shows the structure of the fiber grating cavity (FGC) sensor, which contains two identical FBG's with a Bragg wavelength of λ_B, separated by a short cavity with a length of L_C along a single fiber. If the reflectivity of the two FBG's, $R_G(\lambda)$, is small, the reflection spectrum of the FGC sensor, $R_{\rm FGC}(\lambda)$, is approximately given by

$$R_{\rm GFPC}(\lambda) = CR_G(\lambda)F(\phi) \tag{1}$$

where C is a constant, $F = 1 + A\cos(\phi(\lambda))$, is a cosinusoidal interference function of the phase difference $(\phi(\lambda))$ between the light reflected by the two gratings, and A is a visibility of interference fringes. The phase difference is given by

$$\phi(\lambda) = 4\pi n_C L_C/\lambda \tag{2}$$

where n_C is the effective refractive index of the cavity section. Therefore, the spectral profile of the FGC sensor is determined by the relative positions on the grating's spectrum $R_G(\lambda)$ and the cavity's interference spectrum $F(\lambda)$.

If a minimum of $F(\lambda)$ (at $\lambda_{\rm min}$) occurs within the grating's main reflection band, the FGC spectrum is split into two peaks around $\lambda_{\rm min}$. Once subject to a strain (ε) along or increased temperature (ΔT) at the FGC sensor, both spectra, $R_G(\lambda)$ and $F(\lambda)$, move forward with their respective wavelength shifts, which are given by

$$\begin{aligned}\Delta\lambda_B/\lambda_B &= \beta_1\varepsilon + \alpha_1\Delta T\\ \Delta\lambda_{\rm min}/\lambda_{\rm min} &= \beta_2\varepsilon + \alpha_2\Delta T\end{aligned} \tag{3}$$

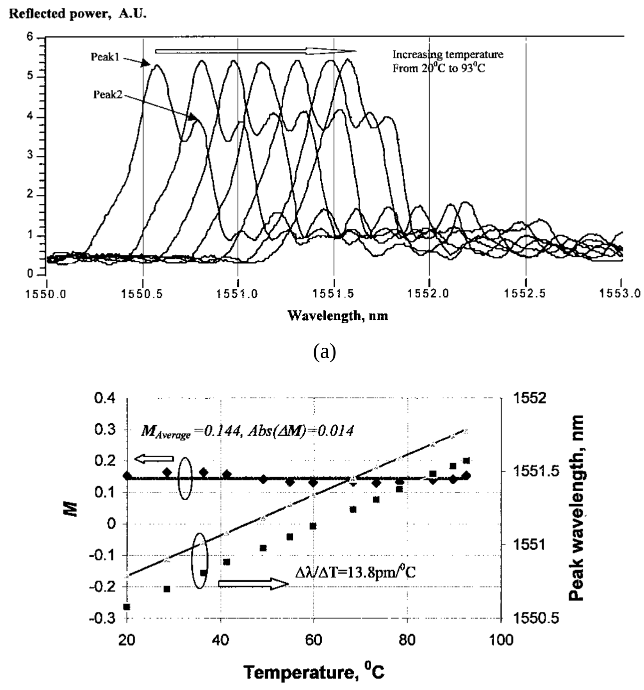

Fig. 2. (a) Measured reflection spectra of the FGTC sensor under different temperature. (b) Relationship between M, peak wavelength, and temperature.

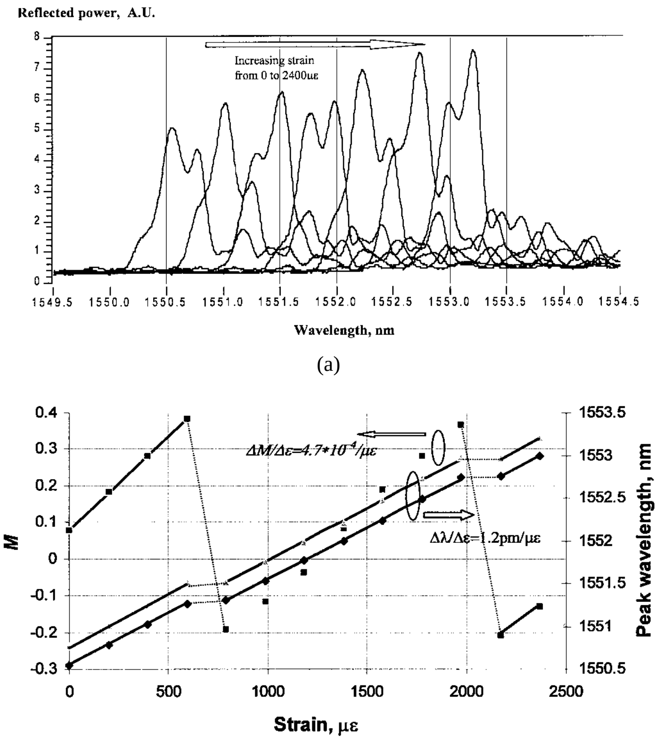

Fig. 3. (a) Measured reflection spectra of the FGTC sensor under different strain. (b) Relationship between M, peak wavelength, and strain.

where β_i and α_i are the strain and temperature coefficients of the grating $(i = 1)$ and cavity $(i = 2)$ sections, respectively. As shown in Fig. 1(a), the grating and cavity sections are made of the same fiber so that $\beta_1 = \beta_2$ and $\alpha_1 = \alpha_2$. Thus, there is no relative movement between the two spectra $R_G(\lambda)$ and $F(\lambda)$, resulting in that the spectral profile of FGC sensor remains unchanged while the whole spectrum shifts with increasing strain or temperature. However, if the grating and cavity sections have different strain or temperature responses, e.g., $\beta_1 < \beta_2$ or $\alpha_1 < \alpha_2$, then $\lambda_{\min}$ moves faster than λ_B. Thus, $\lambda_{\min}$ may become closer to the right side of the grating's main reflection band, resulting in that peak 1 at left grows up and peak 2 at right falls down. Therefore, it is possible to encode the two measurands into the changes in the two spectral peak powers of light reflected from a FGC sensor. In our previous study [6], we glued a thin aluminum tube to the cavity section so that $\beta_1 > \beta_2$ and $\alpha_1 < \alpha_2$. The normalized power difference between the two spectral peaks (I_1 and I_2), which was defined as $M = (I_1 - I_2)/(I_1 + I_2)$, showed a linear dependence upon both strain and temperature. Combining the measurements of the peak wavelength shift and the change in M, the two measurands could be determined simultaneously. However, this aluminum tube structure compromised the integrity of the sensor, which may limit its use in some applications. Fig. 1(b) shows a new and improved structure, i.e., a fiber grating tapered cavity sensor, in which the cavity section is tapered slightly. The maximum change of diameter at the cavity section is smaller than 15%, hence, no obvious changes in transmission and mode effective reflective-index are induced [7]. The tapered cavity section possesses the same strain and temperature coefficients as those of the grating section. However, the average strain suffered by the tapered cavity (ε_C) becomes larger than that at the grating section (ε), which is given by $\varepsilon_C = \rho\varepsilon$, where ρ is an average ratio of cross-sectional areas between the grating and cavity sections.

The relative movement between $F(\lambda)$ and $R_G(\lambda)$ remains zero when the temperature changes, therefore, the spectral profile is only sensitive to the strain applied along the sensor:

$$\begin{aligned}\Delta\lambda_B/\lambda_B &= \beta_1\varepsilon + \alpha_1\Delta T\\ \Delta\lambda_{\min}/\lambda_{\min} &= \rho\beta_1\varepsilon + \alpha_1\Delta T.\end{aligned} \tag{5}$$

In our experiment, a FBG with a length of 5 mm was written in a standard single-mode fiber (Corning-28) with H_2 loading under a uniform phase mask using a KrF_2 excimer laser (at wavelength of 248 nm). The central reflectivity was about 15% at 1550.7 nm. A tapered cavity at the middle of the FBG was created by a fusing-and-pulling treatment with a manual fiber fusion splicer. The width of the arc-fusion spot was about 0.6 mm and the high temperature under fusion erased the grating in the region. A grating tapered cavity structure with one grating (1.9 mm long) at each side and a short cavity (approximately 1.6 mm long) in the middle was fabricated by repeating the fusing-and-pulling treatment for two times. The average diameter of the cavity section was reduced about 13% by controlling the pulling distance when making the tapered cavity. Two spectral peaks were observed within the main reflection band after the cavity was formed.

We tested the responses of a FGTC sensor to temperature and strain separately. Fig. 2(a) shows the result of an experiment in which temperature changes from 20 °C to 93 °C without additional applied strain. The profile of the reflection spectrum remains almost the same while its whole spectrum shifted with increasing temperature. The normalized parameter M and the peak wavelength shifts are plotted against temperature in Fig. 3(b). The maximum deviation of M among all the spectral profiles shown in Fig. 2(a) is 0.014 from the average horizontal line $M = 0.144$, which might be due to un-smooth spectrum of light emitted from the broadband sources used in the experiment. The temperature coefficient is then determined to be $\alpha_1 = 13.8$ pm/°C.

Fig. 3 shows the experimental results of the FGTC sensor's strain response when the temperature was fixed at 20 °C. The evolution of the sensor's reflection spectrum indicates peak 1 (or peak 2) grows up or falls down periodically with increasing strain. Within one period, M and peak wavelength shifts show linear relationship with strain, which are plotted in Fig. 3(b). The strain coefficients are obtained by fitting experimental date using the linear regression

$$\Delta M/\Delta\varepsilon = 4.7 * 10^{-4}/\mu\varepsilon$$
$$\Delta\lambda_{\mathrm{Peak}\,1}/\Delta\varepsilon = \Delta\lambda_{\mathrm{Peak}\,1}/\Delta\varepsilon = 1.2 \text{ pm}/\mu\varepsilon.$$

Consequently, strain can be determined independently by only measuring the change in M since it is independent of the temperature change. On the other hand, temperature change can also be determined by measuring the peak wavelength shift after the strain is measured.

It was noticed that a discontinuity took place at each side of one period [as shown in Fig. 3(b)] when $\lambda_{\min}$ in the cavity's interference spectrum coincided to the right or left tails of the grating's main reflection band. The two adjacent discontinuing points determine the measurable range of strain and maximum change in M, which are approximately 1200 $\mu\varepsilon$ and 0.58, respectively for this particular sensor. Therefore, the deviation of M ($\pm$0.014) due to the temperature change or variation in the spectrum of the light source [Fig. 2(b)] may introduce an error for measuring strain, which is estimated to be $\pm$29 $\mu\varepsilon$. Hence, the maximum change in M and the measurable range of strain are determined by the structural parameters of the cavity sensor such as the grating's reflectivity and bandwidth, cavity's length and tapered angle. Optimization of these structural parameters is critical to obtain larger measurable range for strain and maximize the change of M.

In conclusion, we have reported a spectral-profile encoding method and preliminary experimental result of a novel fiber grating tapered cavity sensor for temperature independent strain measurement.

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