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Simultaneous Temperature and Strain Sensing with Optical Fiber Bragg Gratings

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Abstract: A simple and low-cost fiber grating sensor system designed to simultaneously measure temperature and strain effects is presented. The sensor was constructed with a referenced fiber Bragg for temperature measurement and a pair of fiber Bragg gratings for both temperature and strain detection. Experimental results showed that measurement errors of 0.25 ^oC and 6 $\mu\varepsilon$ for temperature and strain were achieved, respectively.

Keywords: temperature; strain; fiber Bragg grating; sensor

1. Introduction

In recent years, fiber Bragg grating (FBG) has found wide applications ranging from telecommunications to optical fiber sensors. Though FBG sensor has offered potentially a variety of advantages over their conventional counterparts, their widespread use had been plagued by their inability to effectively discriminate between temperature and strain effects. A number of methods to overcome this limitation have been demonstrated [1-7]. Among them, one popular method is to use a separate reference FBG as a temperature sensor. In addition, another popular approach is the dual-wavelength technique involving writing two superimposed FBGs, resulting in the responses to temperature and strain at the same location are different. Therefore, a fiber sensor constructed with both merits of reference FBG and dual-wavelength FBG is expected to achieve excellent strain and temperature performance.

In this paper, a simple FBG sensor called reference dual-wavelength grating sensor that combines a reference FBG with a FBG pair is proposed and studied. Results of simultaneous measurements of strain and temperature effects are reported. Theoretical error analysis and experimental results of the sensor performance for measuring strain and temperature are discussed. Results of the laboratory reliability and long-term stability tests of this sensor mounted on the surface of a concrete specimen for pavement structural monitoring are presented.

2. Experiment and Results

Shown in Fig. 1 is the configuration of the sensor and its detection system, in which the proposed sensor was connected to the output ports of a fiber coupler. Three FBGs at wavelengths of λ_1, λ_2, and λ_3 were interrogated using a broadband ASE light source and an optical spectrum analyzer. The reference FBG was used to measure only the temperature effect:

$$\Delta\lambda_3 = \kappa_{3T}\Delta T \tag{1}$$

The FBG pair was fabricated by splicing two FBGs with reflection peak wavelengths at λ_1 and λ_2, respectively. The wavelength shifts ($\Delta\lambda_i$) from temperature (ΔT_i) and strain ($\Delta\varepsilon_i$) changes can be calculated as:

$$\Delta\lambda_i = \kappa_{i\varepsilon}\Delta\varepsilon_i + \kappa_{iT}\Delta T_i \qquad i = 1,2 \tag{2}$$

where $\kappa_{i\varepsilon} = \partial\lambda/\partial\varepsilon_i$ and $\kappa_{iT} = \partial\lambda/\partial T_i$ are strain and temperature coefficients of the i^{th} fiber grating, respectively. The above equations may be inverted and temperature and strain can be solved as:

$$\begin{pmatrix}\Delta T\\ \Delta\varepsilon\end{pmatrix} = \frac{1}{(\kappa_{1T}\kappa_{2\varepsilon} - \kappa_{2T}\kappa_{1\varepsilon})}\begin{pmatrix}\kappa_{2\varepsilon} & -\kappa_{1\varepsilon}\\ -\kappa_{2T} & \kappa_{1T}\end{pmatrix}\begin{pmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{pmatrix} \tag{3}$$

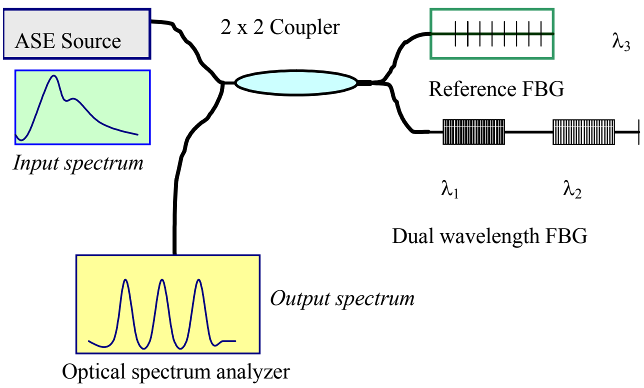

Fig. 1. A reference dual-wavelength grating sensor and its detection system.

It can be seen that the errors in temperature and strain measurement are determined primarily by the resolution of optical spectrum analyzer and the errors in estimation of temperature/strain coefficients. Temperature measured from reference FBG sensor can be used to reduce unnecessary errors induced from the FBG pair and to improve the accuracy of the temperature measurement.

A series of experiments were performed to calibrate every fiber grating used in the sensor. The Bragg wavelengths were chosen such that for the reference FBG of λ_3 is 1551 nm, and for the FBG pair, λ_1 = 1548 nm and λ_2 = 1554 nm, respectively. To calibrate the response of strain, gratings were placed in a controlled thermal environment and external strain variations up to 2600 $\mu\varepsilon$ were applied. The experimental strain coefficient and its calculated error for each grating were determined from the linear response of wavelength shift to applied strain using a linear fit program. The maximum operation range of strain for each grating sensor was also investigated. As shown in Fig. 2, the maximum strain measurement can be up to 5900 $\mu\varepsilon$ for grating with Bragg wavelength at 1548 nm. For grating with wavelength at 1554 nm it was found to be about 4600 $\mu\varepsilon$.

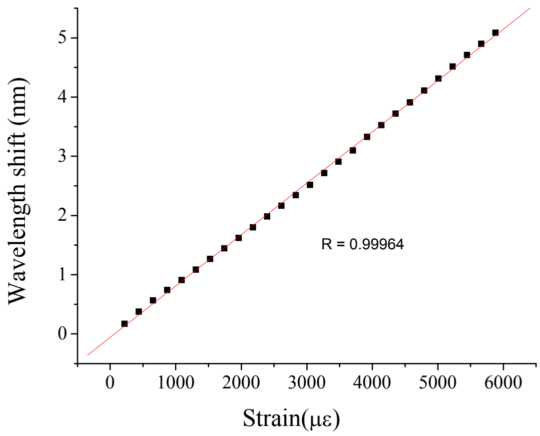

Fig. 2. Wavelength shifts versus applied strain for FBG with Bragg wavelength at 1548nm.

As for the calibration of temperature responses, gratings were kept under strain-free condition and temperature variations up to 150 ^oC were applied. The linear response of wavelength shift to temperature changes was used to calculate the temperature coefficient and its associated error. The fitted strain and temperature coefficients associated with the calculated errors are shown in Table 1. The characteristic matrix of each sensor was then determined and could be inverted to calculate the temperature and strain from the total wavelength shifts induced from external perturbations using equations (1) and (3).

The ability of each grating in the proposed sensor to be used as an independent strain or temperature sensor was first examined. Fig. 3 shows a plot of measured strain as a function of applied strain, in which the applied strain was varied from 100 to 2600 $\mu\varepsilon$ while the temperature was kept constant. The rms deviation of the measured strain from the applied strain was calculated to be 5 $\mu\varepsilon$. It is clear that the sensor performance is limited by the accuracy of the applied strain (~6 $\mu\varepsilon$) and spectral resolution (~0.01 nm). Fig. 4 shows a plot of measured temperature as a function of applied temperature. The applied temperature was varied from room temperature to 80 ^oC while the strain was kept constant. The measurement error of temperature is estimated to be 0.2 ^oC (rms value).

Table 1. Experimental and theoretical errors of individual strain and temperature measurement.

	FBG sensor		
	λ_1 (1548 nm)	λ_2 (1554 nm)	λ_3 (1551 nm)
Strain coefficient (pm/ με)	0.90±0.003	0.92±0.003	N/A
Temperature coefficient (pm/ ^oC)	10.3±0.10	10.5±0.10	12.1±0.08
Theoretical strain error (με)	5.36	4.93	N/A
Experimental strain error (με)	7.86	12.35	N/A
Theoretical temperature error (^oC)	0.17	0.17	0.17
Experimental temperature error (^oC)	0.65	0.44	0.48

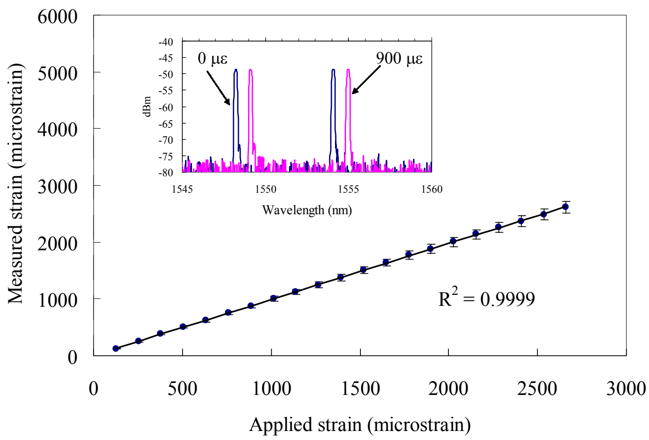

Fig. 3. Measured strain versus applied strain. The inset shows the reflection spectra of the grating sensors at 0 με and 900 με , respectively.

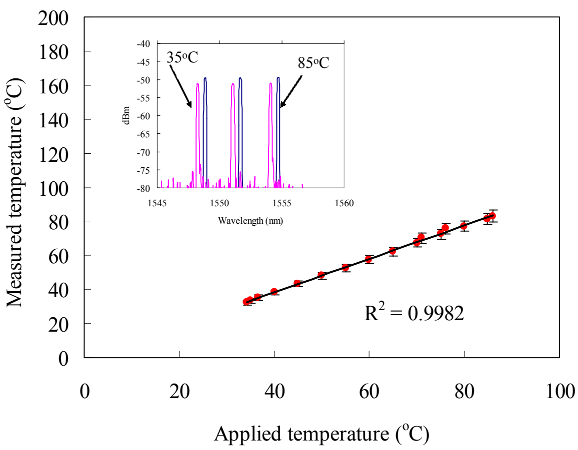

Fig. 4. Measured temperature versus applied temperature. The inset shows the reflection spectra of the grating sensors at 35 ^oC and 85 ^oC , respectively.

For the study of this sensor performance, a series of known temperature and strain were applied, and measured strains and temperatures were determined from the wavelength shift of each grating. Fig. 5 shows the results of simultaneous measurements of strain and temperature. The measured rms errors for temperature and strain were estimated to be 0.25 ^oC and 6 $\mu\varepsilon$, respectively. The sensor performance is again limited by the accuracy of the applied strain (~6 $\mu\varepsilon$) and spectral resolution (~0.01 nm). Table 1 summarized the test results performed to date, including the measured strain and temperature coefficients and their associated errors by theoretical analysis, and experimental and theoretical errors in individual temperature and strain measurements.

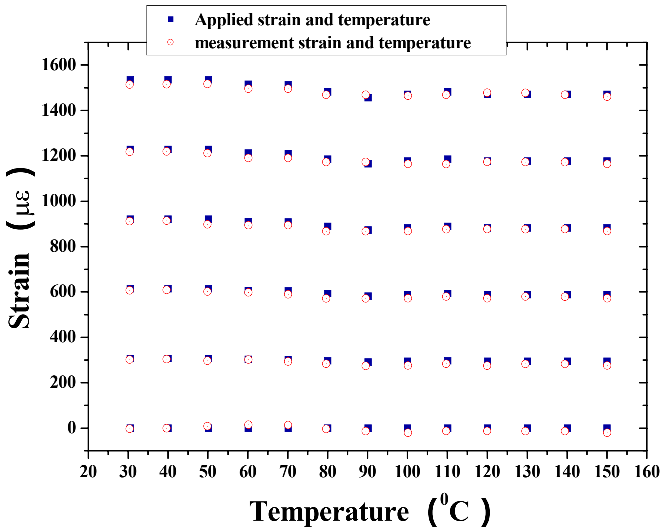

Fig. 5. Results of simultaneous temperature and strain measurement.

Using the error analysis technique presented in Ref. [8], the theoretical strain and temperature errors for the FBG pair were examined. Firstly, we neglected the errors of the measured coefficients and attributed all errors to be caused by errors of measuring λ_1 and λ_2. The maximum errors in temperature T and strain ε were calculated as 0.22 ^oC/pm and 2.47 $\mu\varepsilon$/pm, respectively. Secondly, assuming the maximum errors in all of measured coefficients, the maximum relative errors for temperature ($\delta T/T$) and strain ($\delta\varepsilon/\varepsilon$) were estimated as $0.032+6.51\times10^{-5}\varepsilon/T$, and $7.4\times10^{-4}+0.37T/\varepsilon$, respectively. In Fig. 6, we plotted the experimental relative error of strain $\delta\varepsilon/\varepsilon$ as a function of strain at room temperature (25 ^oC) along with three theoretical curves at temperatures, 25 ^oC, 50 ^oC and 100 ^oC, respectively. It is shown that some measured data exceeded the theoretical calculations, indicating the error in wavelength measurement is not negligible. Finally, considering all the measurement errors in determining the coefficients and wavelength shifts, the errors for $\delta T/T$ and $\delta\varepsilon/\varepsilon$ were estimated as $0.036+0.0032\varepsilon/T$, and $0.036+0.413T/\varepsilon$, respectively. Fig. 7 shows the experimental and theoretical errors of $\delta\varepsilon/\varepsilon$ as a function of strain. It is shown that all the measured data were within the theoretical calculations at a reasonable range through all the applied strain fields.

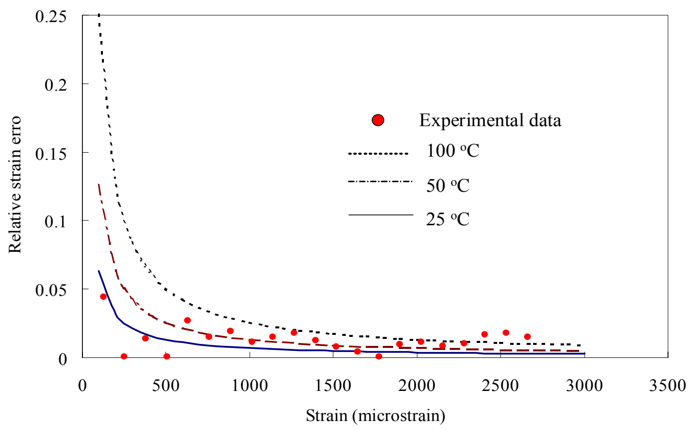

Fig. 6. Measured and calculated relative strain error as a function of strain. In theoretical analysis, the measurement errors in wavelength are neglected.

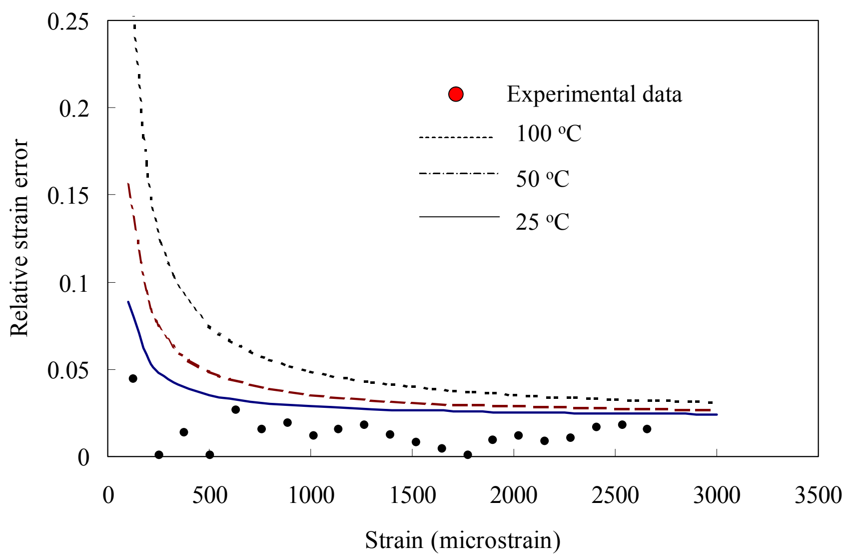

Fig. 7. Measured and calculated relative strain error as a function of applied strain. In theoretical analysis, all measurement errors are taken into account.

3. Application: Concrete Structural Monitoring

To examine the performance of temperature measurement in typical conditions, the proposed FBG sensor and two thermocouples were surface mounted in a concrete specimen for reliability and long-term repeatability tests in the laboratory. One of two thermocouples placed near the location of the sensor was used to compare the temperature performance, while the other thermocouple was used to calibrate the oven temperature. The used plain-concrete specimen was 150 mm (6 inches) diameter and 300 mm (12 inches) height. The maximum aggregate size was 19 mm and type I cement was used to fabricate the cylinder specimens. The 28-day compressive strength of this concrete specimen was 24.15 kPa (3500 psi).

The concrete specimen was placed at a temperature-controlled oven chamber in which the temperature was applied to simulate the typical conditions of field tests. For these tests, several temperature cycles were applied for a long period of time (at least one day). One temperature cycle was carried out by ramping the oven from room temperature up to a designed temperature at a rate of 3 ^oC/hr, and then rapidly down to the room temperature, normally taking 12 hours to finish one cycle. For comparison, a traditional thermocouple was also mounted near the surface of specimens during the testing. The dynamics tests were performed for 48 hours. Fig. 8 shows a plot of temperature variations with time. The rms deviation of temperature variations, δ_{T_O}, measured by this FBG sensor for at least two temperature cycles, when compared to the temperature measured by oven, was ~1.0 ^oC. As for the temperature variations between the FBG sensor and thermocouple, δ_{T_C}, it was found to be about 0.72 ^oC. The maximum temperature variation was 2.9 %. The results showed that the performance of the grating sensor can be comparable with conventional high-resolution thermocouple sensor within our experimental errors.

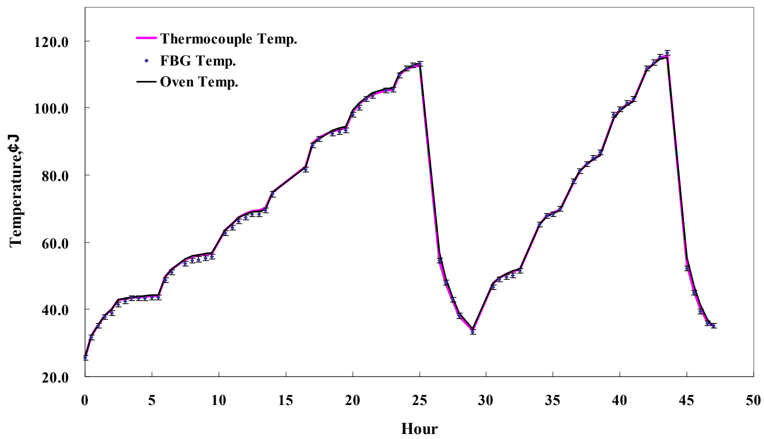

Fig. 8. Repeatability test for the FBG sensor mounted on concrete specimen.

The results of long-term stability tests using this sensor is depicted in Fig. 9, in which the tests were performed at a fixed temperature of 55 ^oC for more than 24 hours. It can be seen that the maximum temperature variations was only 2.2 %, which mainly give rise to the fluctuations of wide loss peak (~0.1 nm) of transmission spectrum. The rms temperature variations, compared to the measurements of oven and thermocouple, were 0.51 ^oC and 0.40 ^oC, respectively. It is obvious that stability tests using grating sensor was better than that of conventional electronic thermocouple. The sensor performance is mainly limited by the accuracy of the applied temperature (~0.5 ^oC) and spectral resolution (~0.1 nm).

The stability performance of this FBG sensor has made it possible to monitor concrete structures under rugged conditions at a reasonable accuracy for a very long period time. This type of sensor can be either embedded inside or bonded to the surface of pavement structures such as asphalt, concrete, steel structures and composite material to monitor directly the internal deformation response within the structures and for non-destructive evaluation of structures. This new, compact and low cost fiber-optic sensor hopefully can benefit the developments and applications of new paving materials, mix design procedures, and/or the enhancement of pavement management system and other infrastructures as well.

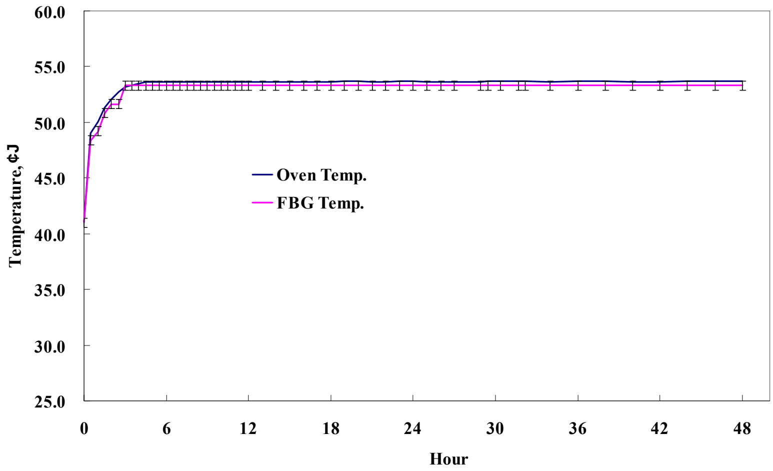

Fig. 9. Stability test for the FBG g sensor mounted on concrete specimen

4. Conclusions

In conclusion, a simple fiber optic grating sensor that combined a reference FBG and a FBG pair was constructed to simultaneously measure strain and temperature fields. Theoretical error analysis and experimental results of the sensor performance are presented. The experimental results indicated those measurement errors of 6 με and 0.25 ^oC for strain and temperature were achieved, respectively.

The reliability and long-term repeatability tests for this sensor were performed by mounting it on the surface of a concrete specimen and several temperature cycles from room temperature to 80 ^oC were applied for at least 24 hours. Small rms temperature variations (less than 1 ^oC) and excellent long-term repeatability and stability (~2 - 3 %) were obtained. The maximum variation of temperature for 48 hours was only 2.2 %. The long-term repeatability and high resolution is of particular important for the detection of slow degenerations within the pavement structures where the time-scale can spread over years and the measurement drifts can easily be ignored by conventional sensors.

Acknowledgements

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