Simultaneous Strain and Temperature Measurement Using a Superstructure Fiber Bragg Grating

Bai-Ou Guan, Hwa-Yaw Tam, *Member, IEEE*, Xiao-Ming Tao, and Xiao-Yi Dong

***Abstract*—A novel and simple fiber-optic sensor based on a superstructure fiber Bragg grating (SFBG) for simultaneous strain and temperature measurement is proposed and demonstrated. The transmission spectrum of the sensor possesses several narrow-band loss peaks situated on the slope of a broad-band loss peak. By measuring the transmitted intensity and wavelength at one of the loss peaks, strain and temperature can be determined simultaneously. The accuracy of the sensor in measuring strain and temperature is estimated to be $\pm 20\,\mu\varepsilon$ in a range from 0 to 1200 $\mu\varepsilon$ and $\pm 1.2\,^{\circ}$C from 20 °C to 120 °C, respectively.**

***Index Terms*—Fiber Bragg grating, long-period grating, simultaneous measurement of strain and temperature.**

I. Introduction

FIBER Bragg gratings (FBG's) have generated much interest for use as sensors to measure strain, temperature, and other physical parameters. However, FBG's are sensitive to strain and temperature, and thus independent measurement of these two measurements using a single FBG is not possible. A number of techniques, such as dual-wavelength superimposed gratings [1], hybrid Bragg grating/long-period grating [2], dual-diameter FBG's [3], FBG superimposed with polarization-rocking filter [4], FBG combined with EDFA [5], and FBG Fabry–Perot cavity method [6], have been proposed to overcome this limitation. Most of them are based on the combination of two FBG's or single FBG with other fiber elements. It is highly desirable to utilize a single sensing element to achieve discrimination between strain and temperature. The FBG Fabry–Perot cavity method recently reported by the authors employed one very short (5-mm) fiber sensor and encode strain and temperature into the power and the Bragg wavelength shift of the reflected light from the sensor to achieve simultaneous measurement of strain and temperature. However, the FBG Fabry–Perot cavity sensor is quite difficult to fabricate. This letter describes a novel and simple fiber sensor based on a superstructure fiber Bragg grating (SFBG) that can measure strain and temperature simultaneously. The SFBG is easy to fabricate and only requires single-step UV exposure.

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II. Principle

The SFBG is a special type of fiber Bragg grating fabricated using periodically modulated exposure over the length of a phase mask. As a periodically modulated FBG, the SFBG couples the forward-propagating LP_{01} mode to the reverse-propagating LP_{01} mode at a series of wavelength and introduces several narrow loss peaks in the transmission spectrum [7]. The SFBG also functions like a long-period grating (LPG) and couples the forward-propagating LP_{01} mode to forward-propagating cladding modes and introduces very broad-band loss peaks in the transmission spectrum. By optimizing the parameters of the SFBG, the narrow loss peaks can be positioned on the slope of one of the broad-band loss peak, as shown in Fig. 1. The wavelength shift of both the narrow-band and broad-band loss peaks are sensitive to strain and temperature, but with different responses. The relative wavelength shift of the broad-band loss peak with respect to the narrow-band peaks changes the intensity of the narrow-band loss peaks. Consequently, strain and temperature can be determined simultaneously from the wavelength and intensity of one of the narrow-band loss peaks in the transmission spectrum. Bhatis *et al.* [8] have demonstrated that the slope of LPG's loss peaks is a logarithmic function of strain and temperature. It can be deduced that the transmitted intensity of an SFBG with the narrow-band loss peaks positioned on the slope of the loss peak is also a logarithmic function of strain and temperature. Therefore, in addition to the shift in narrow-band loss peak wavelength, we now have a second parameter, the transmitted intensity, in decibels, vary linearly with strain and temperature. Therefore, strain change $\Delta\varepsilon$ and temperature change ΔT can be determined simultaneously by solving the following:

$$\Delta I = A\Delta\varepsilon + B\Delta T \tag{1}$$

$$\Delta\lambda = C\Delta\varepsilon + D\Delta T \tag{2}$$

where ΔI is the change in the logarithm of the transmitted intensity and $\Delta\lambda$ is wavelength shift of the narrow-band loss peak. $A\,(C)$ and $B\,(D)$ are the respective strain and temperature coefficients of the loss peak's transmitted intensity (wavelength shift) of the SFBG, which can be determined experimentally by applying strain and temperature separately to the SFBG.

III. Experiment and Discussion

The SFBG was written in a "hydrogen-loaded" Alcatel dispersion-shifted single-mode fiber using a 10-mm-long

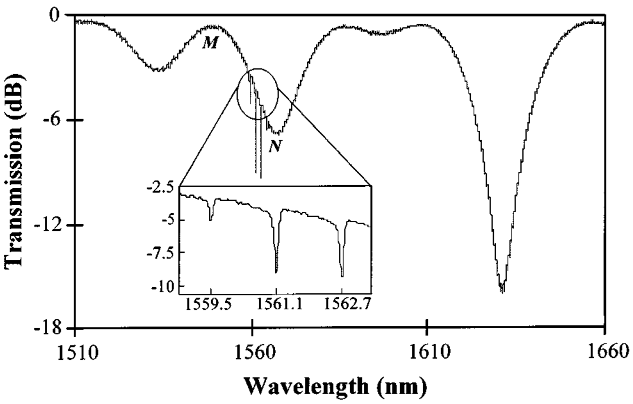

Fig. 1. Transmission spectrum of an SFBG.

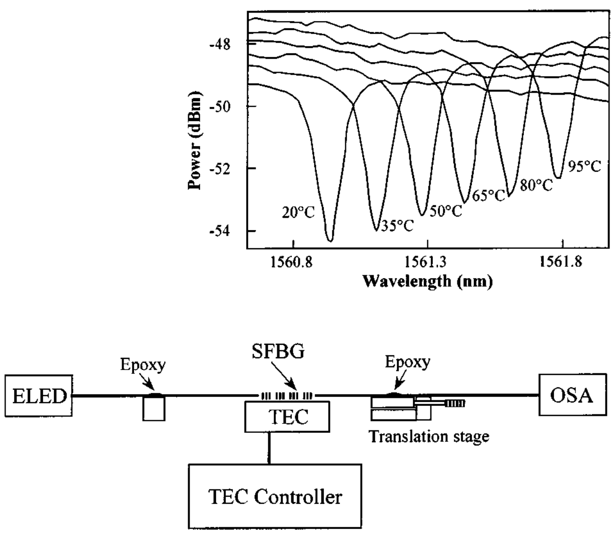

Fig. 2. Experimental setup for determining the strain and temperature coefficients of an SFBG with a 1550-nm ELED and an optical spectrum analyzer. The measured transmission spectrum of the SFBG with temperature varying from 20 to 95 °C with a step of 15 °C is shown in the inset.

uniform phase mask, a 3-cm-long amplitude mask with a period of 500 μm, and an ArF excimer laser. During the writing process, the amplitude mask was placed on top of the phase mask. The 1-cm-long SFBG was then annealed at 160 °C for about 10 h to remove any unreacted hydrogen and unstable UV-induced defects. Fig. 1 shows the transmission spectrum of the SFBG after annealing. The spectrum was measured using a 1550-nm ELED source and an optical spectrum analyzer. Three narrow-band loss peaks are located at the slope of one of the broad-band loss peaks, which has a spectral width of 16 nm centered at 1568 nm. An expanded view of the transmission spectrum of the narrow-band peaks is also shown in the inset of Fig. 1. The spectral width of these peaks is about 0.12 nm and centered at 1559.5, 1561.1, and 1562.7 nm. Any one of these peaks could be used to measure strain and temperature simultaneously. In this work, the 1561.1-nm peak was selected to demonstrate the sensing principle.

The experimental setup for determining the strain and temperature coefficients of the SFBG sensor is shown in Fig. 2. The resolution of the OSA was set at 0.08 nm in all the measurements. The SFBG was placed on top of a thermoelectric cooler

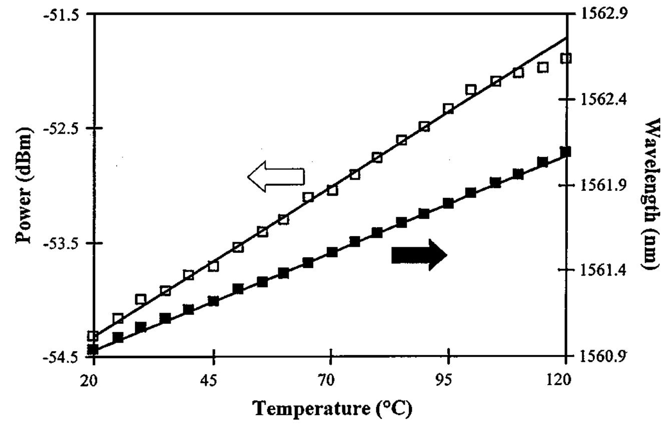

Fig. 3. Relationship between the transmitted intensity, wavelength of the loss peak, and temperature.

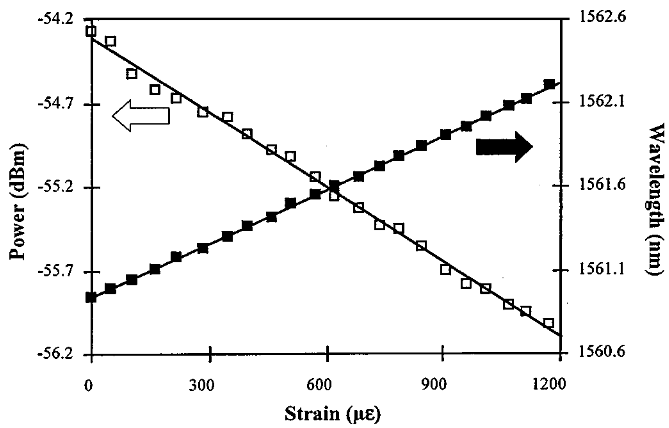

Fig. 4. Relationship between the transmitted intensity, wavelength of the loss peak, and strain.

(TEC) controlled with a TEC controller. The temperature coefficients B and D were measured by heating the sensor, with the TEC, under zero axial strain. The measured transmission spectrum of the SFBG with temperature varying from 20 °C to 95 °C with a step of 15 °C is also shown in Fig. 2. Fig. 3 shows that the transmitted power (in dBm) increases linearly with temperature in the range from 20 °C to about 110 °C. The broad-band spectrum shifts toward the longer wavelength at a faster rate than the narrow-band loss peaks. The wavelength shifts of the broad-band and narrow-band loss peaks with respect to temperature were measured to be 0.08 and 0.01 nm/°C, respectively. This explains the increase in transmitted power as temperature increases. A further increase in temperature shifts the narrow-band loss peak closer to a maximum (labeled as $\boldsymbol{M}$ in Fig. 1) of the spectrum, and thus the transmitted power no longer varied linearly with temperature. The values of B and D were estimated, using linear regression fits, as 0.0261 dB/°C ($R^2 = 0.998$) and 11.3 pm/°C ($R^2 = 0.9995$), respectively, over the range from 20 °C to 110 °C. To measure the strain coefficients, strain was applied to the SFBG by fixing both ends of the grating with epoxy and stretched with a translation stage. The SFBG was maintained at 20 °C with the TEC controller. The measured results are plotted in Fig. 4. The transmitted power (in dBm) and wavelength shift vary linearly with strain over the range from 0 to 1200 $\mu\varepsilon$. The values of A and C were estimated at $-0.001\,48$dB/$\mu\varepsilon$ ($R^2 = 0.9958$) and 1.06 pm/$\mu\varepsilon$ ($R^2 = 0.9996$), respectively. Inserting the values of these coefficients into (1) and (2), strain and temperature can be calculated from the wavelength and intensity of the narrow-band loss peak of the SFBG sensor. From Figs. 3 and 4, the accuracy of this particular sensor in measuring strain and temperature is estimated to be $\pm 20\,\mu\varepsilon$ in the range from 0 to $1200\,\mu\varepsilon$ and $\pm 1.2\,^\circ$C in the temperature range from 20 °C to 110 °C. The measurement range can be extended by using an SFBG sensor element with a broader LPG loss spectrum.

It is interesting to note that the broad-band loss peak shifts toward the shorter wavelength whereas the narrow-band loss peaks shift toward the longer wavelength when the SFBG is stretched. This is because the strain coefficient of long-period grating fabricated in dispersion-shifted fiber is negative [8]. The strain coefficients of the broad-band loss peaks and narrow-band loss peaks of the SFBG were measured to be -2.8 and 1.06 pm/$\mu\varepsilon$, respectively. Therefore, the narrow-band loss peaks move toward point $\boldsymbol{M}$ of Fig. 1 when the sensor experiences an increase in temperature but move toward point $\boldsymbol{N}$ of Fig. 1 when strain was applied to it. Consequently, the measurement range of strain and temperature can be extended at the expense of the other by positioning the narrow-band loss peaks closer to point $\boldsymbol{M}$ (to extent the strain measurement range) or point $\boldsymbol{N}$ (for temperature).

In conclusion, we reported the principle and experimental results of a novel SFBG sensor that allows simultaneously measurement of strain and temperature. This sensor has the advantages of being simple and easy to fabricate. Since it is a transmissive-type sensor, no expensive optical circulator nor lossy 3-dB coupler is needed for the sensing system. However, multiplexing of several sensor elements along a single fiber is not easy to implement due to the broad bandwidth of the loss spectrum of the LPG.

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