Strain-independent Temperature Measurements using a Standard and a Chirped fibre Bragg Grating

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Abstract — **Chirped fibre Bragg gratings (CFBGs) fabricated in hydrogenated plain telecom fibre have a temperature coefficient approximately 20% higher than standard FBGs with identical strain coefficients. Thus a simple technique for strain-independent temperature measurement is proposed.**

I. INTRODUCTION

Considerable research has been devoted to FBG sensors for measuring strain and temperature, particularly for smart structure applications. However the inherent response of FBG sensors to both strain and temperature has complicated independent measurement procedures for these two measurands. Several methods have been proposed and investigated to overcome the problem of cross sensitivity and are well documented [1].

Recently schemes based on dual-grating sensors utilizing the dependence of both temperature and strain sensitivities on grating type have been reported [2]-[4]. All these investigations have exploited the different temperature and similar strain sensitivities of well known grating types (type I, type IIA, type IA) to design sensors either for simultaneous measurement of strain and temperature or strain-independent temperature measurements.

In this work, we report on initial measurements of temperature/strain coefficients of CFBGs and propose a sensor suitable for strain-independent temperature measurements using a combination of a standard and a CFBG.

II. THEORY

Most schemes for strain-temperature discrimination have assumed a linear approximation of the thermal and strain response of FBGs and used the matrix inversion analysis technique to determine the temperature and strain coefficients. This, however, may not be appropriate when wider temperature range is considered as reported in this work.

An analysis technique which takes into account both the nonlinear thermal and linear strain response of the gratings has been proposed [3] In this approach since the strain coefficients of the two gratings are assumed to be approximately the same, the strain independent temperature can be directly measured from the difference in temperature coefficients of the two gratings as

$$\lambda_{B1}(T) - \lambda_{B2}(T) = \sum_{j=0}^{m} K_{1jT} \cdot (T)^j - \sum_{j=0}^{m} K_{2jT} \cdot (T)^j \ , \ (1)$$

where λ_{B1} and λ_{B2} are the corresponding Bragg wavelengths of the two gratings, T is the applied temperature; K_{1jT} and K_{2jT} are the temperature coefficients of the two sensors considering the best order (m) nonlinear polynomial fit to the thermal response of the gratings.

III. GRATING FABRICATION

The gratings used in these measurements were fabricated in hydrogen loaded standard telecommunications Corning SMF-28 fibre. The fibres were hydrogen loaded at approximately 100 atm at 50 °C for 5 days. Standard FBGs (type I) were fabricated using the phase mask technique. The specifications of the phase mask were: Λ_{pm}= 1.059 µm, zero order (< 3%) and the ±1 orders (~38%). Stripped sections of the fibres were exposed for approximately 20 minutes with a CW beam from a 244 nm frequency doubled argon-ion laser operating at approximately 120 mW.

CFBGs were inscribed with a linear chirped phase mask (centre pitch, Λ = 1.0665 µm, chirp rate = 20 nm/cm) using a scanning FBG fabrication system. Stripped sections of fibres were exposed with a CW beam from a 244 nm frequency doubled argon-ion laser operating at approximately 240 mW. Controlled scan rates were used to expose the gratings for approximately 20 minutes. After fabrication, all gratings were annealed at 330 °C for 150 s to improve the repeatability of the measurements. Table 1 shows the parameters of the gratings.

Parameters	Standard FBGs			CFBGs		
	A	B	C	D	E	F
Central Bragg wavelength (nm)	1541.37	1538.42	1542.84	1541.27	1541.27	1541.96
Reflectance (%)	84.5	85.6	84.8	33.2	40.5	30.8
FWHM (nm)	0.8	1.0	0.9	28.2	19.5	28.4
Length (mm)	1.8	1.6	1.5	15	10	15

Table 1   Grating parameters.

IV. EXPERIMENTAL TECHNIQUE

A. Thermal Response

The thermal response of the gratings were obtained using the experimental arrangement shown in figure 1. The gratings were placed inside the central temperature stabilised region of a well calibrated carbolite tube oven with output temperature variation of approximately 2 °C. The gratings were monitored in reflection using an Er^{3+} broadband source via a 3 dB coupler. The unused port was terminated to suppress reflections. Reflection spectra from the gratings were measured using an optical spectrum analyser (OSA) with a resolution of 0.1 nm and saved on a computer via the GPIB interface. Ten measurements were taken at each temperature, both for increasing and decreasing temperature cycles, at an OSA average of 5 and software average of 10. A settling time of approximately 15 min was allowed at each temperature to achieve a thermal equilibrium between the gratings and the oven before measurements. The reflection spectrum data, $R(\lambda)$, were normalized to 14.6 dB above an average measured reflection spectrum of an FC/PC connector and the average Bragg wavelength shift calculated.
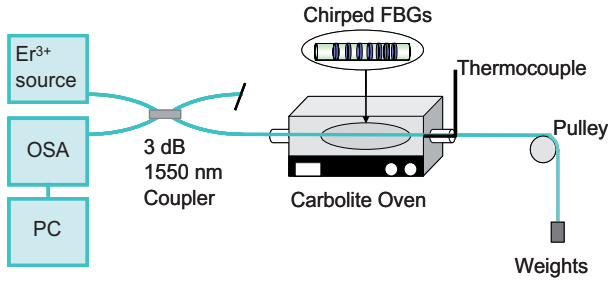

Fig. 1. Schematic diagram of the experimental arrangement to measure temperature and strain response of the sensors.

B. Strain Response

The strain response was measured using the standard technique of applying axial stress to the fibre by hanging weights (mg) to a fibre (Fig.1) and monitoring the shift in Bragg wavelength ($\Delta\lambda_B$). The strain (ε) was calculated from the presumed values of the cross-sectional area (A) and Young's modulus (Y) of the fibre. Weights of 0, 32, 57, 82, 107, 132, 157, 182 and 207 g were applied to the fibre. Strain application was taken through increasing and decreasing cycles to check the repeatability of the measurements. The measurements were repeated at four different oven temperatures of 20, 50, 80 and 100 °C to assess the influence of temperature on the strain response. These measurements were also recorded on a computer.

C. Grating Spectra Analysis

The simplest form of analysing the Bragg wavelength shift due to a measurand is referred to as the 'minima' method [1]. This method, however, is susceptible to resolution limitations and signal noise. Furthermore it involves extracting a single intensity with its corresponding wavelength, which would be unsuitable for the linearly chirped gratings with broadband spectra investigated in this work.

Thus for this work, Bragg wavelength shift was determined using the half-maximum (HM) method [1]. The two HM intensities (50% of the nomalised reflected intensity) are obtained from either side of an array of normalised reflected intensities. These two HM intensity values are then used as an index to interpolate for their corresponding wavelengths from an array of wavelength values and the central Bragg wavelength calculated as the average of the two wavelength values. This method is more accurate as it uses two measurements of wavelengths to calculate the Bragg wavelength shift.

V. RESULTS AND DISCUSSION

A. Thermal Coefficient

Figure 2 shows the variation of the central Bragg wavelength for two gratings (FBG, A and CFBG, D) as a function of temperature under zero axial strain. Shown on the graph are both linear and best higher order polynomial fit to the experimental data. The best polynomial (2nd order) regression for the two gratings can be expressed as

$$\lambda_{BT1}(T) = 6.0 \times 10^{-6} T^2 + 0.00795T + 1541.47 \quad (2a)$$

$$\lambda_{BT2}(T) = 8.5 \times 10^{-6} T^2 + 0.00882T + 1541.41 \quad (2b)$$

where λ_{BT1} and λ_{BT2} are the corresponding Bragg wavelengths (nm) for the standard and CFBGs respectively at temperature, T (°C). The coefficients of determination (r^2), used to evaluate the quality of regression, were 0.999926 and 0.999928 for the above two regressions which were better than linear fit values of 0.996587 and 0.997666.

From the derivative of (2a), the temperature sensitivity of standard FBG, A, is observed to be a function of temperature and varies from 8.21 pm/°C at room temperature of 22 °C to 11.55 pm/°C at 300 °C. Similarly, the temperature sensitivity of CFBG, D, is also a function of temperature and varies from 9.19 pm/°C at room temperature of 22 °C to 13.92 pm/°C at 300 °C, which is about 20% higher than that of a standard FBG. The temperature coefficients of other gratings investigated in this work are shown in table 2.
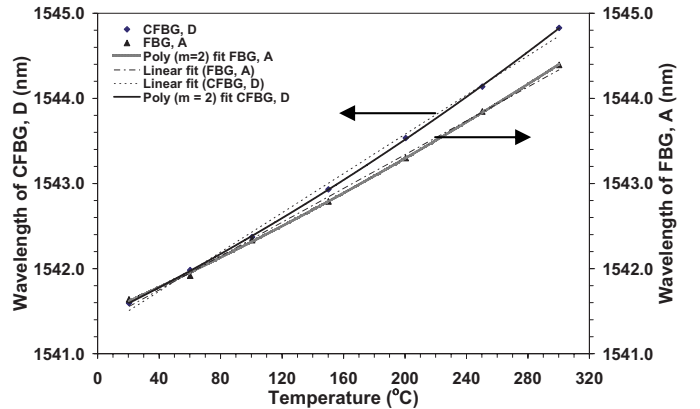

Fig. 2. Central Bragg wavelength vs. applied temperature for the two gratings under zero axial strain. Solid lines represent the best fitted polynomial regression whereas the dotted lines represent the linear fit to the experimental data.

Grating	Temperature Coefficient (± 0.05 pm/°C)		
	Linear fit	Poly. (*m*=2) fit at 22 °C	Poly. (*m*=2) fit at 300 °C
A	9.87	8.21	11.55
B	9.82	8.18	11.57
C	9.84	8.19	11.47
D	11.52	9.19	13.92
E	11.59	9.47	13.70
F	11.68	9.29	13.96

Table 2   Temperature coefficients of the gratings.

B. Strain Coefficient

Figure 3 shows the strain response of the above two gratings at two (22 °C and 100 °C) temperatures. The figure shows that the Bragg wavelength of both gratings is a linear function of applied strain.
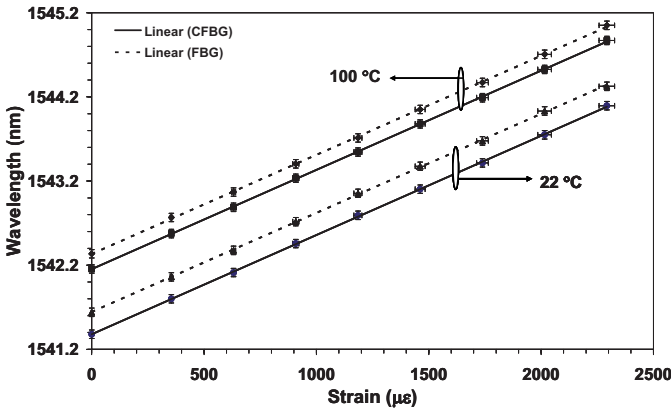

Fig. 3.   Central Bragg wavelength vs. applied strain for the two gratings at two temperatures. Solid lines represent linear fit regression to experimental data for the CFBG whereas the dotted lines represent that of FBG.

Using linear regression, the variation of Bragg wavelength with applied strain for the two gratings at room temperature (22 °C) can be expressed as

$$\lambda_{B\varepsilon 1}(\varepsilon) = 0.001177\varepsilon + 1541.64 \ , \qquad (3a)$$

$$\lambda_{B\varepsilon 2}(\varepsilon) = 0.001179\varepsilon + 1541.38 \ , \qquad (3b)$$

where $\lambda_{B\varepsilon 1}$ and $\lambda_{B\varepsilon 2}$ are the Bragg wavelengths for the standard and CFBG respectively. From (3a) and (3b) it can be verified that the strain coefficients for the two gratings are same (1.18 pm/με) with r^2 values of 0.999816 and 0.999878 respectively. Similar strain coefficients were obtained over the measured temperature range for other gratings.

C. Strain-independent Temperature Measurements

From above, where the strain coefficients of the two gratings have been experimentally verified to be exactly the same over the measured temperature range, the strain-independent temperature can be obtained using the analysis technique proposed by [3]. This can be evaluated by subtracting (2a) from (2b). The resulting calibration equation can be expressed as

$$\Delta\lambda_B(T) = 2.5 \times 10^{-6} T^2 + 0.00087T - 0.06 \ . \qquad (4)$$

From the derivative of (4), the temperature-dependent sensitivity for the measurement varies from 0.98 pm/°C to 2.37 pm/°C at 22 °C and 300 °C respectively. The rms error in strain-independent temperature measurement was calculated to be 2.2 °C and 1.5 °C at 22 °C and 300 °C respectively.

This approach can also be used for simultaneous measurement of strain and temperature. This could be achieved by first solving for temperature from (4). Applied strain can then be evaluated from both set of (2a) and (3a) or (2b) and (3b) by eliminating the temperature effect from the total shift in Bragg wavelength for either one of the sensors.

VI. CONCLUSION

A simple technique for strain-independent temperature measurement is proposed using a sensor head with a combination of a standard and a CFBG. Strain-independent temperature measurement has been demonstrated over the temperature and strain range of 22 – 300 °C and 0 - 2500 με respectively. Temperature dependent sensitivity of 0.98 pm/°C and 2.37 pm/°C for strain-independent temperature measurement with rms errors of 2.2 °C and 1.5 °C at 22 °C and 300 °C respectively has been obtained. Though the large bandwidth of the CFBG may constrain the multiplexing capabilities of the system, the signal processing and system calibration are nevertheless simple. Work is continuing to design a dual grating sensor head consisting of the two gratings. The underlying mechanisms responsible for the higher thermal sensitivity of the CFBGs are yet to be investigated.

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