INTRA-GRATING SENSING WITH A CHIRPED FIBRE BRAGG GRATING USING AN INTEGRATION METHOD

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Abstract

A method to recover arbitrary temperature profiles along a chirped fibre Bragg grating sensor is presented. We demonstrate a nonlinear lookup table method to recover the shape, width and position of a disturbance in temperature after compensating for distortions in the result of integrating changes in the power reflectance spectrum.

Introduction

Fibre Bragg gratings (FBGs) are used as sensors of strain and temperature in materials research and civil engineering. The all fibre construction is convenient to embed in glass and carbon fibre composites and the slim nonconductive cable with long reach presents an attractive advantage to users (Kersey et al. 1997). It is possible to construct a sensor containing a number FBGs of different wavelengths, placed at intervals along a sensor fibre cable. By monitoring the wavelength shifts of each grating with a shared optical spectrum analyser monitoring the transmission spectrum of the sensor fibre cable, the user can obtain point readings of strain and/or temperature at a number of locations. However, each FBG must be separately exposed during fabrication, resulting in an increased cost of the sensor set.

Intra-grating sensing offers measurement of either a strain or temperature profile within a single FBG (Volanthen et al. 1996). The quantity to be measured imposes a change to the spectrum of the FBG. Using the resulting complex spectrum it is possible to apply transforms to recover the profile (Azana and Muriel 2000). However, the required measurement of phase uses delicate apparatus which may not be suited to outdoor and field applications. A more robust system uses only the power reflectance spectrum of a chirped FBG. In this case, the appropriate transformation is a relatively simple integration of changes in the spectrum between a measurement and a reference spectrum taken with uniform strain and temperature.

In this work we show how an integration method enabled extraction of a temperature profile along the length of a chirped fibre Bragg grating. For the first time we demonstrate a method to implement correction to the position-wavelength conversion process according to the extracted wavelength shift, by using a nonlinear lookup table. Using this approach, the position of a temperature peak is determined independent of the magnitude of a temperature or strain profile.

Materials and Methods

A chirped FBG was fabricated by UV exposure of SMF-28 fibre which had been hydrogen loaded at 200 atm. A 1 mm diameter UV beam of 240 mW power was scanned along the fibre at 1 mm per minute through a chirped phase mask. The interference pattern behind the phase mask was imprinted on the photosensitive fibre, resulting in a flat topped grating of 8% reflectance after annealing at 330 °C for 3 minutes (Nand et al. 2006).

The sensor had a length of 18 mm and its chirp, at a rate of 18 nm/cm, enabled each location in the grating to be assigned a unique wavelength. The power spectrum returned from an erbium broadband source to an optical spectrum analyser via a 50:50 coupler was recorded and compared to a reference trace taken under conditions of known uniform temperature and strain.

The sensor was tested by touching an electrically heated wire to it at right angles, and allowing convection cooling in equilibrium to maintain a hotspot of 2 mm length along the sensor. The resistance of the nichrome heater wire was monitored to allow an estimate of its temperature assuming a coefficient of resistivity of 0.0004 °C (Lide 2006).

Analysis

Wherever a temperature gradient was applied to the sensor, the local chirp rate was altered, resulting in a change to the reflected power in that region of the spectrum. Integrating such power changes provides a temperature profile which is
continuous along the sensor (Kitcher et al. 2006). In this method, which we summarise below, the measured reflectance \( R(\lambda) \) of each measurement was linearised to units of grating coupling strength \( Y(\lambda) \) according to (1) including normalization, using (2), against the reference trace \( R_{ref}(\lambda) \).

\[
\bar{Y}(\lambda) = \tanh^{-1}(\sqrt{R(\lambda)}) \quad (1)
\]

\[
Y(\lambda) = \bar{Y}(\lambda) \frac{\int Y_{ref}(\lambda')d\lambda'}{\int \bar{Y}(\lambda)d\lambda} \quad (2)
\]

By applying a Chebyshev low pass filter of 1 nm bandwidth, the 50% point in the rising edges of the reference and data were found to a precision of less than 5% of the 0.04 nm point spacing. The shift \( S \) in this edge was determined. The change to the spectra was integrated using (3) to provide an estimate of local wavelength shift \( Q(\lambda) \) across the measured spectrum. The limits of the integration from the rising edge point \( \lambda_i \) to \( \lambda \) define a cumulative sum over \( \lambda' \), which is a dummy variable for the \( \lambda \) of the integration in (3).

\[
Q(\lambda) = S - 2.2 \lambda \int_{\lambda_i}^{\lambda} \frac{Y(\lambda'-S) - Y_{ref}(\lambda')}{Y_{ref}(\lambda')} d\lambda' \quad (3)
\]

However, the fine ripples in the spectrum \( Y(\lambda) \) were shifted in relation to \( Y_{ref}(\lambda) \) and these resulted in minor inaccuracy in the method. We resolved this by using the first estimate of \( Q(\lambda) \) from (3) to interpolate a shifted \( Y(\lambda'-Q(\lambda)) \) and then repeating the integration through the use of (4) with this improved alignment.

\[
Q(\lambda) = S - 2.2 \lambda \int_{\lambda_i}^{\lambda} \frac{Y(\lambda'-Q(\lambda')) - Y_{ref}(\lambda')}{Y_{ref}(\lambda')} d\lambda' \quad (4)
\]

The resulting \( Q(\lambda) \) indicated the local wavelength shift caused by heating according to (5) which provides the scale factor \( d\lambda/dT \) of 10.2 nm/°C to convert to temperature. Using the known chirp rate \( C \) of the grating, the wavelength axis could be used to estimate the location of each wavelength point. However a linear calculation using \( C \) resulted in temperature profiles which became increasingly skewed and shifted as heater power increased. An improved estimate was provided by using (6) as a lookup table to interpolate position \( Z \) along the grating from wavelength, taking into account the extracted wavelength shift \( Q \) as well as the chirp rate \( C \).

\[
Q(\lambda) = (T - T_{ref}) \frac{d\lambda}{dT} \quad (5)
\]

\[
\lambda_B(Z) = \lambda_{centre} + \mu C(Z - Z_{centre}) + Q(\lambda) \quad (6)
\]

**Results and Discussion**

Power reflectance spectra of the chirped intra-grating sensor are shown in Fig. 1 when the device was subjected to heater powers of 0, 1 and 2 W. Locating the heater wire at the position in the grating corresponding to 1545 nm resulted in the dip and rise in the spectrum caused by ascending and descending thermal gradients which increased and decreased the grating chirp, respectively. In the region of decreasing temperature, the region of the grating which was originally at 1548 nm remained at 1548 nm. The region of the grating which was originally at 1547 nm was heated by at least 100 °C, resulting a 1 nm thermo-optic shift so that it added to the reflected power at 1548 nm (Fig. 1).
Fig. 1  Power reflectance spectra of an 18 nm/cm chirped FBG subjected to a hotspot at the location corresponding to 1545 nm at the indicated heater powers.

Applying the integration method described above to the spectra of Fig. 1 resulted in the corresponding temperature profiles shown in Fig. 2.

Fig. 2  Extracted temperature profiles at the indicated heater powers, obtained using the described integration method.

The expected hotspot was recovered from the spectra as shown in Fig. 2. Despite the considerable difference in widths of the spectral disturbances at heater powers of 1 W compared with 2 W (Fig. 1), the widths and shapes of the recovered profiles were consistent (Fig. 2). For both 1 and 2 W of heater power the location of the maximum was at 1.5 mm from the centre of the grating, corresponding to 1545 nm. This demonstrates the improvement offered by use of (6) to recover position from a nonlinear lookup table. By comparison, other authors have used linear methods assuming the original chirp rate of the grating, which does not account for the profile induced shift in wavelength. For example, this would result in profiles which are shifted and distorted by greater than 1 mm for the data analysed in this paper.
The peak temperatures extracted by our integration method were approximately 100 and 220 °C. These were lower than the temperatures inferred from the wire resistance of 210 and 355 ± 20 °C, respectively. A plausible explanation for this difference is that the sensor was located in the core of the fibre, one side of which was in contact with the wire and the other side was in contact with air at room temperature. Therefore the sensor will be at a lower temperature than the wire, as was observed.

Conclusions
We have demonstrated an intra-grating temperature profile sensor employing a chirped fibre Bragg grating and an integration method. Experimental results using a heating wire provided a measured temperature increase in the fibre core with heater power which was, as expected, lower than the temperature increase of the wire. We report for the first time a nonlinear lookup table method which resulted in recovery by an integration method of consistent locations, widths and shapes of temperature profiles.

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References