Submitted to 842.
OFS'10
Glasgow, 1994

Simultaneous Measurement of Strain and Temperature Using Fibre Grating Sensors

M. G. Xu, J.-L. Archambault, L. Reekie and J.P. Dakin

Optoelectronics Research Centre, University of Southampton
Southampton SO17 1BJ, United Kingdom

Abstract

Spectral behaviour of strain and thermal sensitivities of two superimposed fibre gratings of two different Bragg wavelengths has been studied. This involves monitoring the Bragg wavelength as a function of strain and temperature on the gratings. The results show that the ratio of sensitivity at two different Bragg wavelengths (850 nm and 1300 nm) is different with strain and temperature, which can be used for simultaneous measurement of these parameters in fibre grating sensors.

Introduction

Considerable research effort has been devoted to fibre Bragg grating sensors, which are particularly well suited for measuring strain in smart structures[1]. However, undesirable temperature sensitivity of the fibre grating sensor may complicate its application as a strain gauge.

On a single measurement of the Bragg wavelength shift, it is impossible to differentiate between the effects of changes in strain and temperature. It has been suggested that temperature can be measured and compensated using a second grating element contained within a different material and placed in series with the first grating element[2]. Also thermal effects can be well-compensated using a pair of fibre gratings in a certain configuration[3]. Two-parameter scheme, measuring two different wavelengths or two different optical modes, allows some discrimination between strain and thermal effects[4,5]. An extended set of parameters can be obtained using dispersive Fourier transform spectroscopy[6].

In fibre grating sensors, to resolve these two effects it is logical to measure two different Bragg wavelengths, nevertheless, little is known about the ratio of sensitivity at two Bragg wavelengths with relation to strain and temperature. It is important to understand this dependence, and in this paper we present the initial results of our recent studies of this effect.

Principle

Assuming that the strain-and thermally-induced perturbations are linear, the Bragg wavelength change $\Delta\lambda_\varepsilon$, in response to a strain change $\Delta\varepsilon$, at constant temperature, can be expressed as:

$$\Delta\lambda_\varepsilon = K_\varepsilon \Delta\varepsilon \qquad (1)$$

where $K_\varepsilon = \partial\lambda/\partial\varepsilon$ is related to the Poisson's ratio of the fibre, components of the strain-optic tensor, and the effective refractive index of the fibre core. Similarly, the thermally-induced Bragg wavelength shift $\Delta\lambda_T$, due to a change in temperature ΔT, may be given by:

$$\Delta\lambda_T = K_T \Delta T \qquad (2)$$

where $K_T = \partial\lambda/\partial T$ is determined by the thermal expansion coefficient and the thermooptic coefficient. In general, the change in Bragg wavelength $\Delta\lambda_B$, of the fibre grating, can be expressed as:

$$\Delta\lambda_B(\varepsilon, T) = K_\varepsilon \Delta\varepsilon + K_T \Delta T \qquad (3)$$

This assumes that the strain and thermal response are essentially independent, ie. the related strain-temperature cross-term is negligible, a behaviour which has already been found to apply well for small perturbations[1]. As a result, for the two Bragg wavelengths to be measured, the following relation holds:

$$\begin{pmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{pmatrix} = \begin{pmatrix} K_{\varepsilon 1} & K_{T1} \\ K_{\varepsilon 2} & K_{T2} \end{pmatrix} \begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} \qquad (4)$$

where 1 and 2 refer to the two wavelengths. As the photoelastic and thermo-optic coefficients are wavelength dependent, wavelength changes of each of the two superimposed gratings will be different although each grating is subject to the same level of strain. In other words, this suggests a way of simultaneous measurement of strain and temperature, or compensation for the temperature during strain measurement. The elements of the **K** matrix can be determined experimentally by separately measuring the Bragg wavelength changes with strain and temperature. Once **K** is known, changes in both strain and temperature can be determined using the inverse of equation 4 provided that the matrix inversion is well-conditioned.

Experiment and Discussion

The key sensing elements are the superimposed fibre gratings, with nominal Bragg wavelengths of ~1298nm and ~848nm, peak reflectivities of ~70% and ~55%, and optical bandwidths of ~0.9 nm and ~0.45 nm (FWHM), respectively. The experiment is shown in Fig.1. Light from the 850nm and 1300nm ELED's, of bandwidth (FWHM) ~56nm, was split via two corresponding fibre couplers to the gratings and the light reflected from the two fibre gratings was monitored using a commercial optical spectrum analyzer (ANDO AQ-6310B).

Strain was applied using a micrometer driven stage and temperature measurement results were obtained using a Peltier heat pump and a thermistor controlled by a thermoelectric temperature controller. For convenience of demonstrating the concept, the four elements of the **K** matrix were obtained by separately measuring the Bragg wavelength of each fibre grating, for changes in strain only and subsequently for changes in temperature only. Linear regression analysis gave correlation coefficients of ≥0.998 for all four relationships for a strain range of 0-800 μstrain and a temperature range of 10-60°C. The measured values of the **K** elements were:

$$K_{\varepsilon 1} = 0.96 \pm 6.58 \times 10^{-3}\ pm/\mu strain \quad K_{T1} = 8.72 \pm 7.7 \times 10^{-2}\ pm/{}^\circ C$$
$$K_{\varepsilon 2} = 0.59 \pm 3.45 \times 10^{-3}\ pm/\mu strain \quad K_{T2} = 6.30 \pm 3.7 \times 10^{-2}\ pm/{}^\circ C$$

which gives for the determinant of **K** a standard error of 7.4%, thus the matrix is well-conditioned.

Table.1 shows the comparison of measured values and those predicted from the matrix inversion. Typical errors were around 10 microstrain and ±5°C for the measurement range of 800 microstrain and 50°C. The inaccuracy of the larger temperature excursions can be attributed to the limited resolution of the spectrum analyser and strain and temperature measurement range. Using a more accurate interrogating system, which is currently under development, we would expect to improve the matrix conditioning and thus achieve higher sensitivities for the wavelength measurement.

Conclusion

We have demonstrated the feasibility of simultaneous measurement of strain and temperature using two superimposed fibre gratings. Work is being directed towards extending the strain and temperature measurement range, to improving the measurement resolution using a more accurate interrogating system.

Acknowledgements

The ORC is a U. K. government funded (SERC) Interdisciplinary Research Centre.

References

1. Morey, W.W., Meltz, G., and Glenn, W.H.: "Fibre optic Bragg grating sensors". Proc. SPIE, Vol.1169, 1989, pp.98-107.
2. Morey, W.W., Meltz, G., and Welss, J.M.: "Evaluation of a fiber Bragg grating hydrostatic pressure sensor". Proc. OFS'8, Monterey, 1992, Postdeadline Paper PD-4.4
3. Xu, M.G., Archambault, J.-L., Reekie, L., and Dakin, J.P.: "Thermally-compensated bending gauge using surface-mounted fibre gratings", to be published in Int. J. Optoelectronics.
4. Farahi, F., Webb, D.J., Jones, J.D.C., and Jackson, D.A.: "Simultaneous measurement of temperature and strain: cross-sensitivity considerations", J. Lightwave Technol., Vol.8 No.2, 1990, pp.138-142.
5. Culshaw, B., and Michie, C.:" Fibre optic strain and temperature measurement in composite materials- A review of the OSTIC programme", Proc. Int. Symp. on Advanced materials for lightweight structures, ESTEC, Noordwijk, March, 1992, pp.393-398.
6. Flavin, D.A., McBride, R., and Jones, J.D.C.: "Simultaneous measurement of temperature and strain by dispersive Fourier transform spectroscopy", Proc. OFS'9, Florence, 1993, pp.333-336.

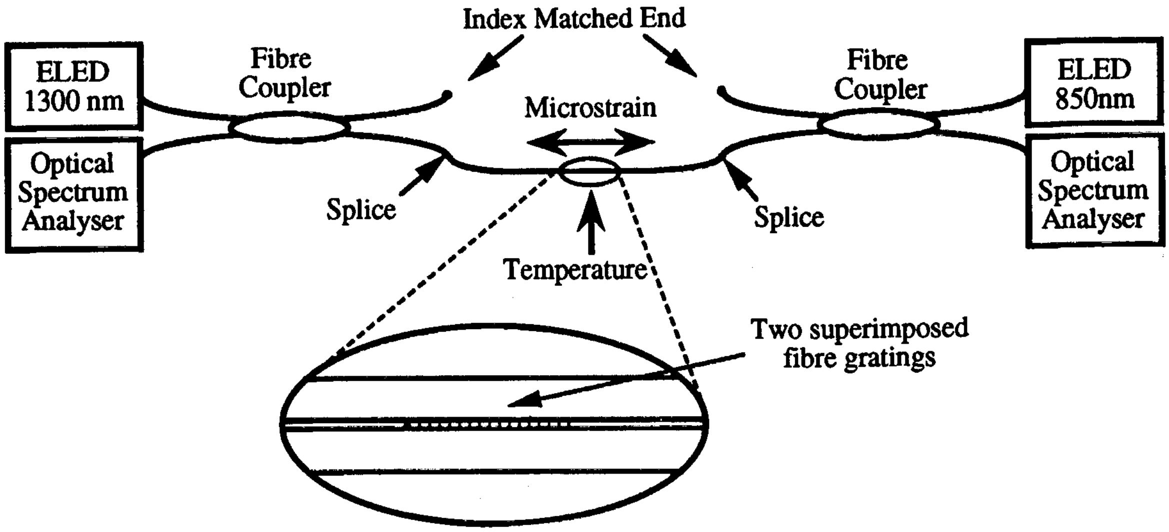

Fig.1 Experimental Setup of Simultaneous Measurement of Strain and Temperature Using Two Superimposed Fibre Graings

Readings	Measured Values		Predicted Values	
	Δε (με)	ΔT (°C)	Δε (με)	ΔT (°C)
1	62	2.1	58	6.9
2	185	2.1	176	7.1
3	244	3.2	235	5.4
4	244	1.8	235	7.9

Table 1. Comparison of Measured Values and Those From Matrix Inversion