Thermally-Compensated Bending Gauge Using Surface-Mounted Fibre Gratings

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Abstract

A novel thermally-compensated bending gauge using surface-mounted fibre Bragg gratings is demonstrated. The gauge configuration involves two fibre Bragg gratings, surface-mounted on opposite surfaces of a bent mechanical structure. Experimental results using a cantilever beam are presented, showing a strain resolution of 9 μstrain.

Introduction

Surface-mounted optical fibre strain gauges are showing promise for real-time monitoring of structural integrity[1,2]. Engineering applications where it is required to measure strain at a point benefit from having a strain gauge of small dimensions. Fibre Bragg grating sensors are particularly well suited for measuring either strain, pressure and temperature[3,4]. Engineering systems in which it is desired to monitor bending are often addressed by determining the surface strain in a bent structure. However, undesirable temperature sensitivity of the fibre grating strain sensor may complicate its application as a strain gauge. The majority of fibre-grating sensor work presented so far has centred more on the signal recovery (ie. interrogation of measurand-induced wavelength shift) and less on the sensors themselves. Accordingly, many publications have either appeared to ignore the cross sensitivity, or have reported results at "constant temperature". In this paper, we present a novel yet simple method of compensating for ambient temperature changes using a surface-mounted fibre grating pair. As a result of this arrangement, a well-compensated bending gauge is possible.

Principle

We shall now describe the theory of the method. We shall initially consider a simple strain gauge based on a fibre grating. Making the simplifying assumption that the fibre is mechanically homogeneous and that the material is isotropic, the fractional change, $\Delta\lambda_g/\lambda_g$, induced in the Bragg wavelength, λ_g, in response to a strain change, $\Delta\varepsilon$, is given by[3]:

$$\frac{\Delta\lambda_g(\varepsilon)}{\lambda_g}=\left(1-\frac{n^2}{2}[(1-\mu)p_{12}-\mu p_{11}]\right)\Delta\varepsilon \tag{1}$$

where μ is Poisson's ratio of the fibre, p_{11} and p_{12} are components of the strain-optic tensor, and n is the effective refractive index of the fibre core. It should be noted that eqn.(1) is only valid when a straight fibre segment is exposed to a strain field. In general, the Bragg wavelength increases when the fibre grating is strained and decreases when compressed (ie.$\Delta\varepsilon<0$).

If the fibre is attached to the surface of a cantilever beam, the far-end beam deflection, d, can be converted to strain in the fibre gratings[1]. This strain, $\varepsilon(x)$, is a function of the distance, x, from the free end of the cantilever, the cantilever length, l, and the distance, a, from the neutral axis:

$$\varepsilon(x)=\frac{3dax}{l^3} \tag{2}$$

If we now consider two fibre gratings, surface-mounted on opposite surfaces (top and bottom) of the cantilever beam, one fibre grating will be longitudinally stretched, while the other will be compressed when the free end of the beam is vertically deflected as shown in Fig.1. As the fibre grating is sensitive to both strain, ε, and temperature, T, the instantaneous Bragg wavelength, λ_g, of the fibre gratings can be expressed as:

$$\lambda_g(\varepsilon,T) = \lambda_g(0) + \Delta\lambda_g(\varepsilon) + \Delta\lambda_g(T) \tag{3}$$

where $\lambda_g(0)$ is the nominal Bragg wavelength (ie. unstrained and at room temperature),$\Delta\lambda_g(\varepsilon)$ is the strain-induced Bragg wavelength shift and $\Delta\lambda_g(T)$ is the thermally-induced Bragg wavelength changes. If two fibre gratings have the same thermal sensitivity and the mechanical beam on which they are surface-mounted is a good thermal conductor, then the difference in Bragg wavelength is thermally-independent. ie:

$$\lambda_{g1}(\varepsilon,T) - \lambda_{g2}(\varepsilon,T) = 2\,|\Delta\lambda_g(\varepsilon)| \tag{4}$$

for simplicity, we have assumed that the two fibre gratings are identical.

Experiment and Discussion

Our experimental system is shown in Fig.1. Light from a broadband optical source (ELED) was split, via a fibre coupler, to both fibre gratings, each surface-mounted on the cantilever beam. The light reflected from the fibre gratings was monitored by a commercial optical spectrum analyzer (ANDO AQ-6310B). The broadband source used was a 1300 nm single-mode fibre-pigtailed ELED, which launched ~50 μW of output power over a ~56 nm bandwidth (FWHM). The two fibre gratings had nominal Bragg wavelengths of ~1310.99 nm and ~1311.30 nm, peak reflectivities of ~90% and ~95%, and optical bandwidths of ~0.4 nm and ~0.45 nm (FWHM), respectively.

The mechanical test apparatus consisted of a 30-cm cantilever beam, with four surface-mounted resistance strain gauges (two on each side of the beam), a micrometer screw to displace the free end of the cantilever, and a commercial precision strain indicator (M-3800E) to interrogate the resistance gauges, which is sold specially as a calibrator for strain gauges.

The commercial electrical strain gauge system was configured using a thermally-compensated bridge for each sensor. It was therefore only sensitive to the bending-induced strain, with essentially no thermal response. The cantilever beam was installed in an oven to allow measurements over a range of temperatures.

As the length of the fibre gratings was small (~3 mm), the strain field can be assumed to be constant over the entire grating region. The length over which the fibre sensor was bonded to the surface was approximately 80 mm, with the grating in the middle. This additional bonding-line length was used to ensure that the main transfer of strain (via bonding-line shear) occurs in the extremes of the bonded section so that the grating suitably observes the strain in the metal surface. However, the strain read by the resistance gauge is the bending-induced strain at the surface of the beam, but the strain in the fibre grating is slightly larger due to its increased distance from the beam's neutral axis. In our case, this increase is negligible, as the beam thickness is 6 mm compared to only 58 μm fibre radius, and also the fibre does not significantly reinforce the beam.

Using a value of 0.17 for Poisson's ratio, and values of 0.121 and 0.270 for p_{11} and p_{12}, respectively, for fused silica and a value of 1.465 for the refractive index of the germania-doped core, we predict that the **fractional** wavelength shift is 0.78 times the strain $\Delta\varepsilon$. In our first experiment, for convenience of demonstrating the concept, differential results were obtained by separately measuring $\Delta\lambda_{g1}(\varepsilon,T)$ and $\Delta\lambda_{g2}(\varepsilon,T)$.

The sensitivity to which we can measure the wavelength shift will depend to a large extent on the Bragg grating bandwidth. With the grating and optical spectrum analyser we used for this test, we could measure the Bragg wavelength to about 0.01 nm and thus the strain to a resolution of 9 μstrain. Using a more accurate analyser or interrogating system, one could achieve higher sensitivities for the wavelength measurement[5].

The experimentally measured values of strain sensitivity at the temperatures of 21.7°C is 1.0287 picometer/μstrain, which is in excellent agreement with the value of 1.031 picometer/μstrain predicted by theory in eqn.(1), (2) and (4). The measured strain sensitivity at 49.7°C is 1.0463 picometer/μstrain, 2% greater than that at 21.7°C. This is likely due to strain effects caused by the difference in thermal expansion coefficients between the structure (beam) and the sensor (fibre gratings).

Fig.2 shows that each fibre grating responds strongly to temperature change. However, the differential response (ie. the difference between the Bragg wavelengths) is insensitive to temperature and responds only to bending strain, as shown in Fig.3. Clearly, our results show that the effects of temperature on our own fibre optic bending gauge is negligible, despite each individual strain sensor having considerable thermal sensitivity.

Conclusion

We have demonstrated a new thermally-compensated bending gauge, using surface-mounted fibre Bragg gratings. These are bonded on opposite surfaces of a cantilever beam. The experimental results were found to be in excellent agreement with the expected strain sensitivity. It has been shown that the configuration provides excellent thermal compensation.

Acknowledgements

The ORC is a U. K. government funded (SERC) Interdisciplinary Research Centre. The programme has been supported by ESA/ESTEC research centre, Noordwijk, NL. The authors would also like to thank Mr M. Deegan of Measurements Group U.K. Ltd. for the loan of the strain calibrator.

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Figure captions

Fig.1 Schematic diagram of experiment arrangement (note that electrical strain gauges are mounted in the beam adjacent to both our fibre gauges)

Fig.2 Experimental strain results from both fibre gratings at the two different temperatures

○ and ◊ upper strain sensor (fibre grating stretched)

• and ◆ lower strain sensor (fibre grating compressed)

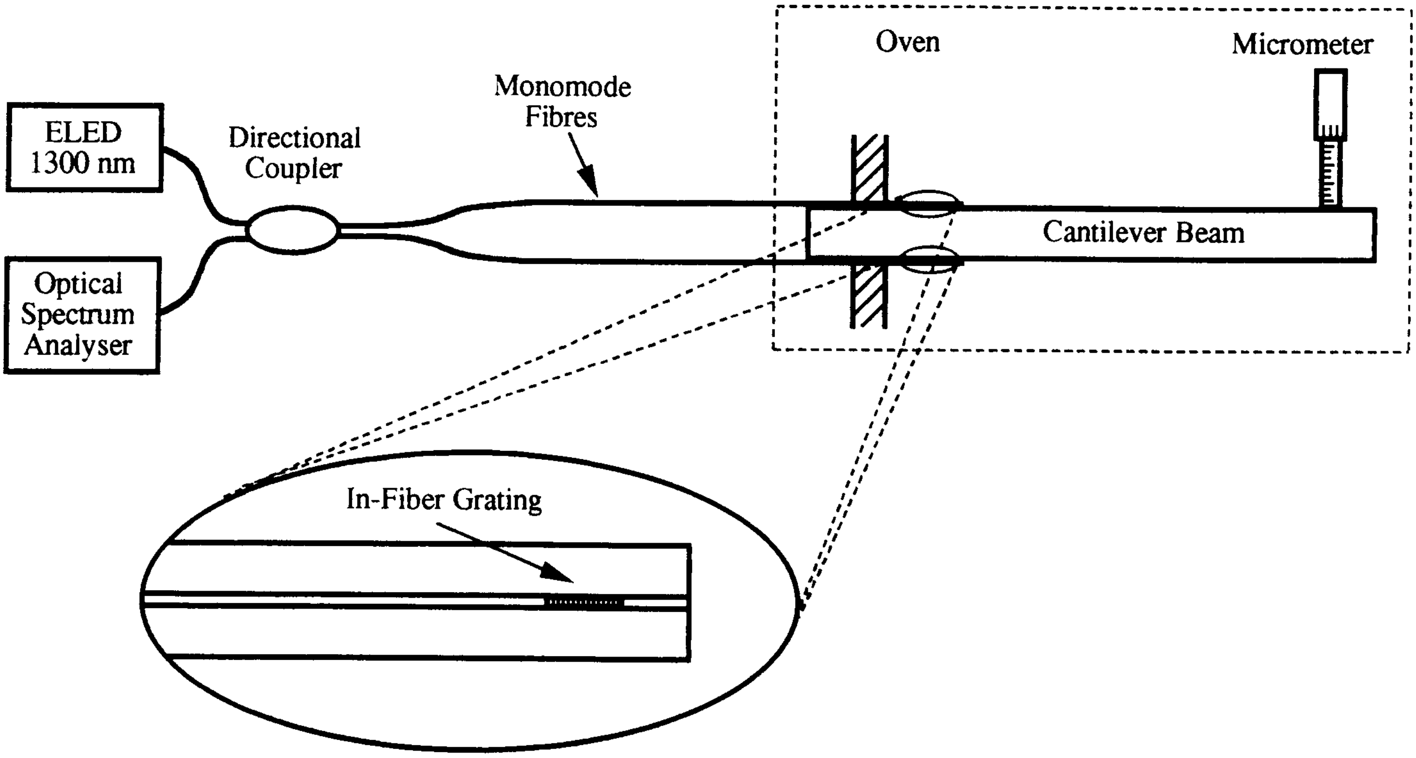
— linear fit

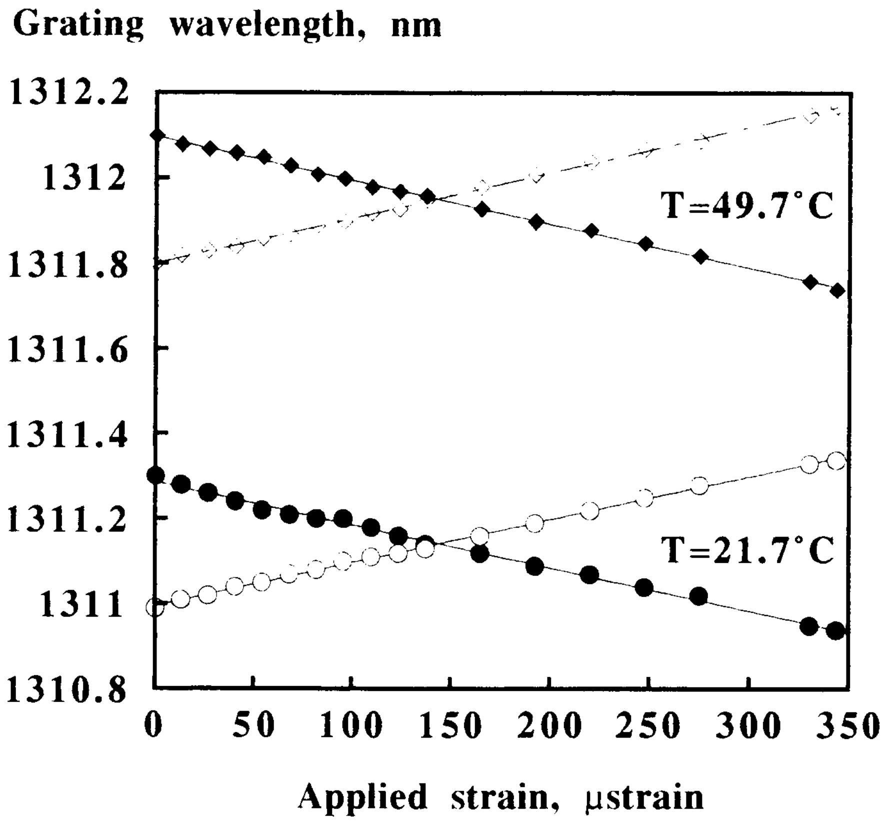
Fig.3 Differential Bragg wavelength strain results with the temperature difference of 28°C

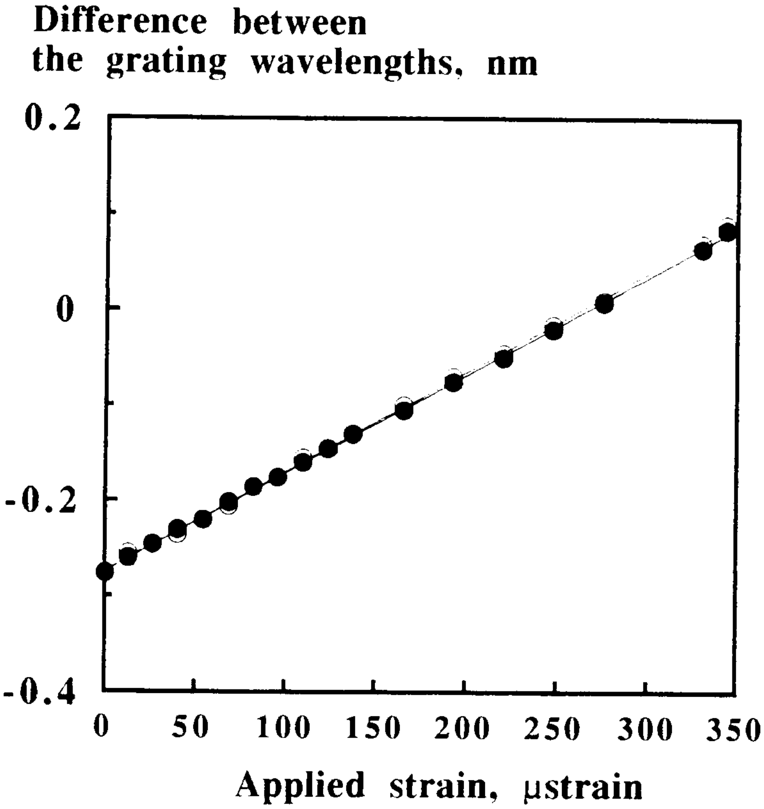
• Results at 21.7°C showing the strain sensitivity of 1.03 pm/μstrain

○ Results at 49.7°C showing the strain sensitivity of 1.05 pm/μstrain

— linear fit


Oven
Micrometer
Monomode
Fibres
ELED
1300 nm
Directional
Coupler
Optical
Spectrum
Analyser
Cantilever Beam
In-Fiber Grating


Grating wavelength, nm
1312.2
1312
1311.8
1311.6
1311.4
1311.2
1311
1310.8
T=49.7°C
T=21.7°C
0
50
100
150
200
250
300
350
Applied strain, μstrain


Difference between
the grating wavelengths, nm
0.2
0
-0.2
-0.4
0
50
100
150
200
250
300
350
Applied strain, µstrain