Differential phase tracking applied to Bragg gratings in multi-core fibre for high accuracy curvature measurement

G.M.H. Flockhart, G.A. Cranch and C.K. Kirkendall

High resolution quasi-static and dynamic curvature measurements are made by differential interferometric phase measurement of fibre Bragg gratings in separate cores of a multi-core fibre. A DC curvature stability of $1 \times 10^{-3}\,\mathrm{m}^{-1}$ and an AC curvature resolution of $1 \times 10^{-4}\,\mathrm{m}^{-1}/\mathrm{Hz}^{1/2}$ are reported.

Introduction: Strain measurements within structures are often used to determine structural deformation; bending is inferred from the measured strain. In applications where multiple curvature sensors are required along a single fibre, sensors based on fibre Bragg gratings (FBGs) have the potential to be multiplexed in large numbers. FBG strain gauges can measure bending by measuring differential strain in a structure [1]. Two-axis curvature measurement using FBGs has also been demonstrated [2]. A more robust and compact curvature sensor can be fabricated by writing FBG strain gauges into three cores of a multi-core fibre (MCF) [3]. However, the small core separation requires improved strain measurement. Quasi-static measurements are possible using differential interferometric interrogation and resolutions of 6 $\mathrm{n}\varepsilon/\mathrm{Hz}^{1/2}$ at 1 Hz have been demonstrated in conventional singlemode fibre [4]. In this Letter we report the application of interferometric interrogation for differential strain sensing in separate cores of an MCF for high resolution quasi-static and dynamic curvature measurements.

Experiment: The MCF consists of four singlemode Ge-doped cores arranged in a square with a core separation of ~50 µm and a circular cladding diameter of 125 µm. An argon-ion laser and a uniform period phase mask were used to fabricate similar gratings in all cores of the MCF. The FBGs are ~6 mm in length, exhibit Bragg wavelengths between 1550.53 and 1551.77 nm, and strengths from 1 to 4 dB in transmission.

Fig. 1 is a schematic of the experimental system to measure the induced differential strain. The output from an erbium broadband source (BBS) is launched into a fibre-optic Mach-Zehnder interferometer (MZI) with a 3.6 ± 0.2 mm optical path imbalance. The two outputs available from the MZI are each injected into a separate core of the MCF and circulators are used to direct the reflected signals from the gratings onto two photodetectors. A phase generated carrier (PGC) demodulation technique [5] is then used to extract the interferometric phases. The phase change, $\Delta\phi$, is linearly proportional to the applied strain, $\Delta\varepsilon$, on the FBG sensor [4]. Using a refractive index $n = 1.468$ and if we assume a wavelength-normalised strain sensitivity of 0.78 [6] and a Bragg wavelength of 1551 nm, the responsivity is $\Delta\phi/\Delta\varepsilon = 16.7\,\mathrm{mrad}/\mu\varepsilon$.

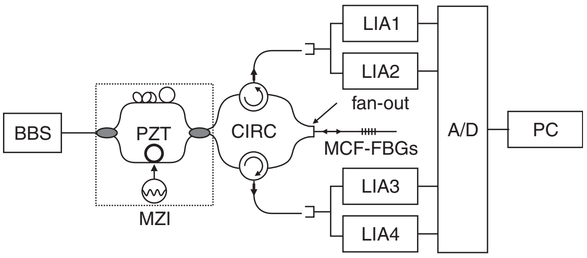

Fig. 1 *Experimental setup for curvature measurement*

The bending test rig comprised a cantilever beam formed by a brass tube of outer diameter 1.6 mm. The FBGs were recoated and inserted into a tightly fitting PTFE tube which was then inserted into the cantilever beam. The PTFE tubing ensured the fibre took the shape of the cantilever beam when deflected. The FBGs were located 3.5 ± 1 mm from the fixed end of the cantilever beam. The cantilever was displaced by two orthogonal motorised micrometers at a distance of 200 ± 1 mm from the fixed end. This configuration allows small curvatures to be applied independently along two axes; however this arrangement does not produce constant strain along the length of the fibre. There will be a small variation in strain along the length of the FBG which will induce a chirp in the grating period. This effect will be of equal magnitude but of opposite sign for the FBGs in tension against compression.

Results: The differential strain between gratings in two adjacent cores was investigated. The MCF was orientated to produce a maximum differential strain when the cantilever was displaced in the vertical or y-direction. The cantilever beam was displaced in steps of 1 mm in the y-axis up to a maximum of 5 mm and then returned to the start point. The bend sensitivity in the horizontal plane was also measured to investigate the fibre alignment. The phase difference between cores for displacement in the y-axis is shown in Fig. 2*a*. The phase difference at each displacement step is plotted against the applied displacement for the y-axis in Fig. 2*b*; linear polynomial fits were applied to the differential phase against displacement in both the x- and y-axes. The azimuthal orientation of the sensor was determined to be 8°, from the arctangent of the ratio of the phase sensitivity with displacement for bending in x (8.34 rad/m) to bending in y (59.04 rad/m). For the bending configuration used here this is equivalent to a phase sensitivity with respect to curvature of $0.7933\,\mathrm{rad/m^{-1}}$. This compares well with the theoretical value of $0.8268\,\mathrm{rad/m^{-1}}$, the ~4% variation is within the calibration accuracy of the interrogating interferometer.

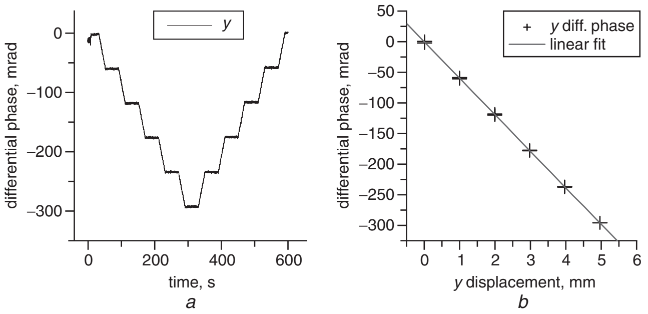

Fig. 2 *Measured phase difference against time for displacement in y-axis, and phase difference against applied displacement in y-axis with linear fit*

a Measured phase difference against time for displacement in y-axis
b Phase difference against applied displacement in y-axis with linear fit

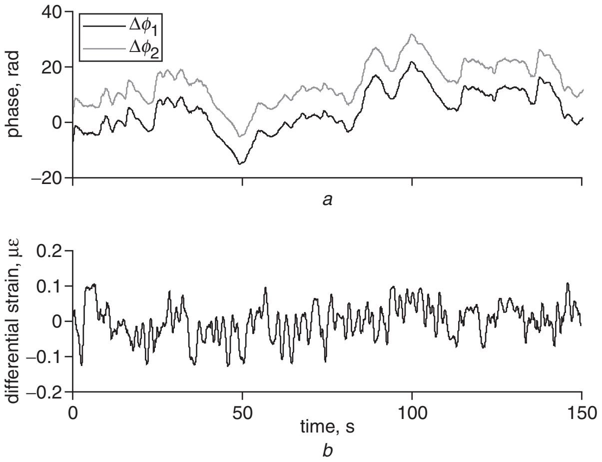

Fig. 3 *Phase drift with DC offset, and differential strain noise with 1 s filter width*

a Phase drift with DC offset
b Differential strain noise with 1 s filter width

The DC drift of the sensor and interrogation system were recorded with a sampling frequency of 7.5 kHz. The measured phase for each grating, with an arbitrary DC phase offset, are shown in Fig. 3*a* and clearly show large variations, ~30 rad, against time. The primary cause of these variations is the sensitivity of the MZI and optical fibre downlead to environmental perturbations; however perturbations in the MZI are common to the interrogation of both gratings. Thus the differential phase yields a much smaller variation. The differential strain has been calculated from the differential phase which was lowpass filtered using a running average of duration 1 s and is plotted in Fig. 3*b*. This plot clearly indicates a very high differential strain stability with an rms deviation of 0.05 $\mu\varepsilon$, which is equivalent to a curvature of $1 \times 10^{-3}\,\text{m}^{-1}$ for an unperturbed sensor and measurement system. However in environments where the interferometer and sensor downlead are perturbed the measurement accuracy will be degraded. Birefringence fluctuations in the interferometer and downlead result in increased drift owing to a combination of the degree of polarisation of the BBS, birefringence in the sensing grating and any polarisation-dependent loss in the system [7]. These affects can be reduced by reducing the degree of polarisation of the source.

Dynamic curvature measurements have also been demonstrated by applying a displacement to the cantilever beam with a piezoelectric actuator with a 5 Hz modulation frequency. Fig. 4 shows the power spectrum of the measured phase converted to strain for each core and the calculated differential strain. The signal at 5 Hz is clearly evident in all three signals. Note that other low frequency effects above and below 5 Hz are also clearly cancelled. The AC differential strain resolution is approximately $5\,\text{n}\varepsilon/\text{Hz}^{1/2}$ corresponding to a phase resolution of $84\,\mu\text{rad}/\text{Hz}^{1/2}$, which is equivalent to a curvature resolution of $1 \times 10^{-4}\,\text{m}^{-1}/\text{Hz}^{1/2}$.

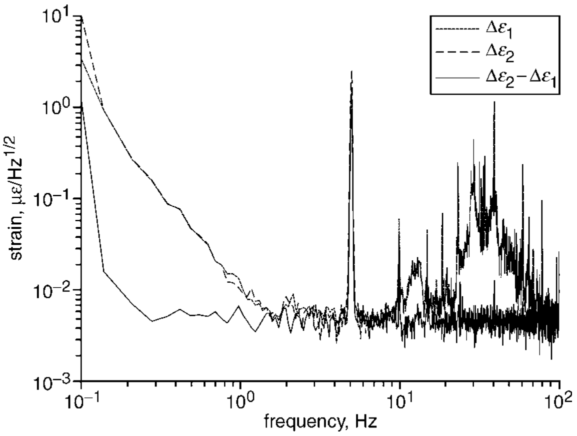

Fig. 4 *Sensor response to 5 Hz applied curvature*

Conclusion: We have applied a differential interferometric demodulation technique to differential strain sensing in a multi-core optical fibre. This interrogation technique can be readily modified to allow efficient multiplexing of many FBGs in each core [8] and a simple coupler tree would allow simultaneous interrogation of three or more cores for two-axis curvature measurement.

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References

1 Xu, M.G., Archambault, J.L., Reekie, L., and Dakin, J.P.: 'Thermally-compensated bending gauge using surface-mounted fiber gratings', *Int. J. Optoelectron.*, 1994, **9**, (3), pp. 281–283

2 Araujo, F.M., Ferreira, L.A., and Santos, J.L.: 'Simultaneous determination of curvature, plane of curvature, and temperature by use of a miniaturized sensing head based on fiber Bragg gratings', *Appl. Opt.*, 2002, **41**, (13), pp. 2401–2407

3 Flockhart, G.M.H., MacPherson, W.N., Barton, J.S., Jones, J.D.C., Zhang, L., and Bennion, I.: 'Two-axis bend measurement with Bragg gratings in multicore optical fiber', *Opt. Lett.*, 2003, **28**, (6), pp. 387–389

4 Kersey, A.D., Berkoff, T.A., and Morey, W.W.: 'Fiberoptic Bragg grating strain sensor with drift-compensated high-resolution interferometric wavelength-shift detection', *Opt. Lett.*, 1993, **18**, (1), pp. 72–74

5 Dandridge, A., Tveten, A.B., and Giallorenzi, T.G.: 'Homodyne demodulation scheme for fiber optic sensors using phase generated carrier', *IEEE J. Quantum Electron.*, 1982, **18**, (10), pp. 1647–1653

6 Borrelli, N.F., and Miller, R.A.: 'Determination of individual strain-optic coefficients of glass by an ultrasonic technique', *Appl. Opt.*, 1968, **7**, (5), pp. 745–750

7 Cranch, G.A., Flockhart, G.M.H., and Kirkendall, C.K.: 'Polarization properties of interferometrically interrogated fiber Bragg grating and tandem interferometer strain sensors', *J. Lightwave Technol.*, 2005, **23**, (11), p. 3798

8 Cranch, G.A., Flockhart, G.M.H., and Kirkendall, C.K.: 'Efficient fiber Bragg grating and fiber Fabry-Perot sensor multiplexing scheme using a broadband pulsed mode-locked laser', *J. Lightwave Technol.*, 2005, **23**, (11), pp. 3798–3807