# Tunnel monitoring using multicore fiber displacement sensor

William N. MacPherson, M. Silva-Lopez, James S. Barton, A. J. Moore, J. D. C. Jones, et al.

William N. MacPherson, M. Silva-Lopez, James S. Barton, A. J. Moore, J. D. C. Jones, D. Zhao, Lin Zhang, Ian Bennion, Nicole Metje, C. D. F. Rogers, David N. Chapman, "Tunnel monitoring using multicore fiber displacement sensor," Proc. SPIE 5855, 17th International Conference on Optical Fibre Sensors,  (23 May 2005); doi: 10.1117/12.623992

Event: 17th International Conference on Optical Fibre Sensors, 2005, Bruges, Belgium

# Tunnel Monitoring using Multicore Fibre Displacement Sensor

W.N. MacPherson[a], M. Silva-Lopez[a], J.S. Barton[a], A.J. Moore[a], J.D.C. Jones[a], D. Zhao[b], L. Zhang[b],
I. Bennion[b], N. Metje[c], C.D.F. Rogers[c], D.N. Chapman[c]

[a] School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK
[b] Photonics Research Group, Electronic Engineering and Computer Science Division, Aston University, Birmingham B4 7ET, UK
[c] Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK

## ABSTRACT

We describe the first application of multiplexed fibre Bragg grating strain sensors in a multicore fibre. Sets of gratings, acting as strain gauges, are co-located in the multicore fibre such that they enable the curvature to be measured. Multiple sets of these gratings allow the curvature to be measured at several points along the fibre. This sensor is configured to monitor displacement of concrete tunnel sections, and was demonstrated capable of displacement measurement with a resolution of ±0.1 mm over a range of several millimeters.

Keywords: Multicore, fibre Bragg grating, optical fibre, bend sensing, structural monitoring

## 1. INTRODUCTION

Structural monitoring is becoming increasingly important not only because of new materials and processes, but also to monitor older structures that are susceptible to decay. In this work we consider a possible technique for on-line monitoring of displacement between tunnel segments. This is of vital importance for tunnels that may be subject to changing forces, due to nearby building activity for example[1]. Monitoring tunnel parameters over extended distances and in real-time poses a significant measurement challenge.

Optical fibre sensors are often cited as potential monitoring techniques for such applications due to their immunity to electrical interference, minimal intrusiveness, safety in hazardous environments, and their capability to offer multiplexed sensor architectures[2]. In particular the fibre Bragg grating (FBG) has been extensively reported for structural monitoring applications[3,4]. However, in general the FBG suffers from two key disadvantages: it is temperature sensitive in addition to strain sensitive, and the strain transfer from the structure to the sensor is not always simple. Whilst the temperature sensitivity may be corrected by using compensation gratings[5], it is desirable to have a sensor that is inherently temperature insensitive. It is often more difficult to address the issue of strain coupling from the structure to the fibre. For example creep may arise between the fibre and the structure due to slippage between adhesive and the fibre, or between the cladding and the buffer coating (if the buffer has not been removed).

In this paper we describe a sensor based upon monitoring the *shape* of a simple cantilever that is attached across the join between two tunnel sections in a laboratory test facility. The design of the sensor is such that the curvature is recovered by considering pairs of measurements co-located in a single multicore fibre, therefore the design is insensitive to common-mode temperature effects. Furthermore, the sensor measures shape rather than strain experienced by the structure, hence the issue of strain transfer between structure and fibre is eliminated. However, it is essential that the fibre accurately follow the shape of the cantilever for reliable results.

## 2. MULTICORE FIBRE CURVATURE SENSOR

The multicore fibre used in this experiment is fabricated from a standard fused silica preform that is drilled to accept four boron co-doped silica rods that form the cores when drawn into fibre. These holes are arranged such that in the final fibre the cores are arranged at the vertices of a square with 50 μm side length. The overall fibre diameter is 125 μm, and is shown in figure 1. Each core is singlemode at 1550 nm and separated sufficiently such that no core-core interaction is observed.

The intrinsic photosensitivity of this multicore fibre permits UV-inscription of the FBG structures in the cores without hydrogenation of the fibre – an essential treatment for grating fabrication in standard telecom fibre and the non-circular four-core fibres that we have used in previous work[6]. We have produced high-efficiency FBGs in this multicore fibre using the standard phase mask scanning technique[7] and a frequency doubled Ar laser with a 95 mW output at 244

17th International Conference on Optical Fibre Sensors, Marc Voet, Reinhardt Willsch,
Wolfgang Ecke, Julian Jones, Brian Culshaw, eds., Proceedings of SPIE Vol. 5855
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.623992

nm. In the fabrication, the UV beam was scanned at a speed of 0.07 mm $s^{-1}$ over a 10mm length of the fibre. In order to write gratings selectively on the cores, we mounted the fibre on a rotation stage to accommodate the setting of the fibre orientation. Both single- and double-exposure methods were employed to write grating structures in one or more cores. The latter involves a second UV exposure to the fibre after it being rotated by 180° following the first exposure.

The FBG's act as localised strain sensors and, when the fibre is bent, they sample the strain about the neutral axis (see figure 2). By comparing pairs of gratings it is possible to obtain the magnitude of the curvature, and the plane containing the bend. In this way orthogonal pairs of gratings can give a measure of curvature in orthogonal planes. We have previously demonstrated this configuration for curvature measurement in 1 and 2 dimensions[8,6], however in this paper we report the use of two multiplexed gratings per core (8 gratings in total) to measure the shape of a simple cantilever. With this measurement we can determine the displacement of the end of the cantilever, thus offering a means of displacement measurement.

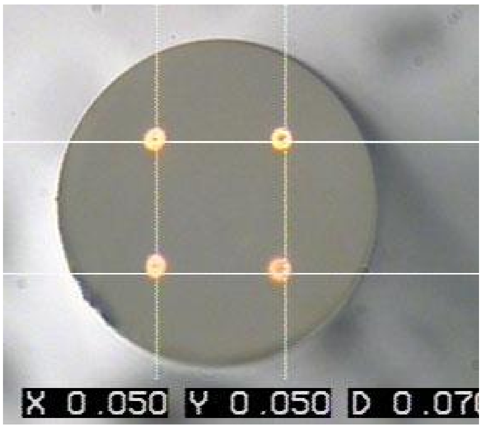

**Figure 1** Cross section of MCF used in this experiment. The cores have been illuminated with white light and are located on a square with side length 50 μm.

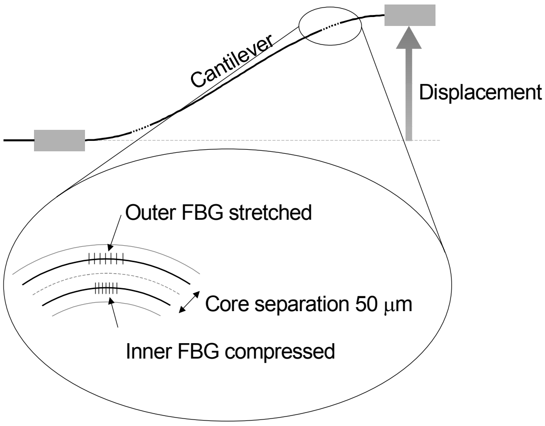

**Figure 2** FBG pairs act as curvature sensors - the curvature is determined using the difference between the gratings.

## 3. DISPLACEMENT SENSOR DESIGN

Our test application requires a sensor that can be retrofitted with minimal intrusion. We have chosen to use a thin stainless steel tube (0.3 mm inside diameter and 1.6 mm outside diameter) as a cantilever that is fixed across the gap between tunnel sections. As the relative position of the section changes, the cantilever is distorted. Measuring this distortion give a means of determining the displacement of the tunnel section.

The cantilever is attached to the tunnel section via mounting blocks that act as rigid supports for the cantilever. If we consider the case of simple translation of one end of the cantilever, then the cantilever shape is given by[9]

$$w(x) = 12\frac{\delta}{L^2}\left(\frac{x^2}{4} - \frac{x^3}{6L}\right) \tag{1}$$

where $w(x)$ is the displacement of the cantilever at a point $x$ along the cantilever of length $L$. $\delta$ is the translational displacement applied to one end of the cantilever. For small deflections (i.e. for small values of the first derivative of $w(x)$) then the curvature at any point along the cantilever is given by the second derivative of $w$,

$$w''(x) = 12\frac{\delta}{L^2}\left(\frac{1}{2} - \frac{x}{L}\right) \tag{2}$$

Therefore measurement of curvature at a known point along the cantilever enables the displacement $\delta$ to be determined, and these quantities are plotted for our cantilever model with a 3 mm deflection in figure 3. Any angular change between the two tunnel sections can also be determined, but this requires a second curvature measurement on a suitable point on the cantilever. The actual cantilever is shown in figure 4, attached to the tunnel lining using two mounting blocks. In our test the blocks were 20 mm cubes, however in a final design this size could be reduced to an overall thickness of only a few mm. In our cantilever the FBG's are located approximately 10 mm from each mounting point. In this way simple translation will result in curvature with opposite sign measured at each set of gratings whereas an angular change will be result in curvature of the same sense at both sets of gratings, thus it is possible to measure both translation and angular change simultaneously.

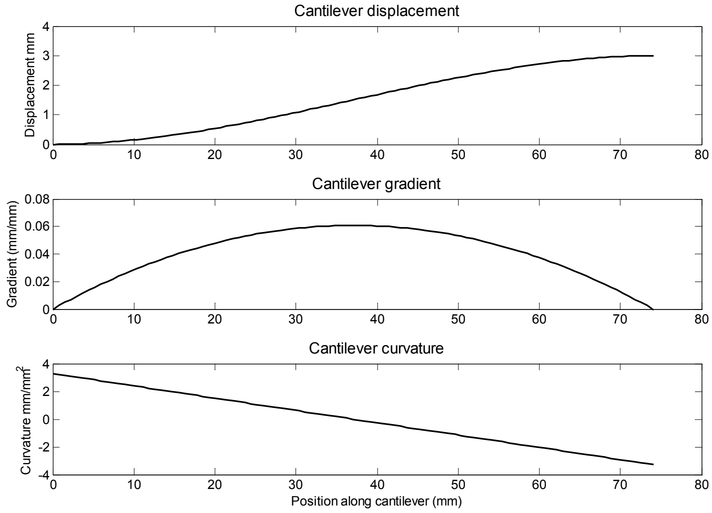

Figure 3 Model of cantilever shape, gradient and curvature for an applied displacement of 3mm. Note that the curvature at each end of the cantilever is of opposite sign.

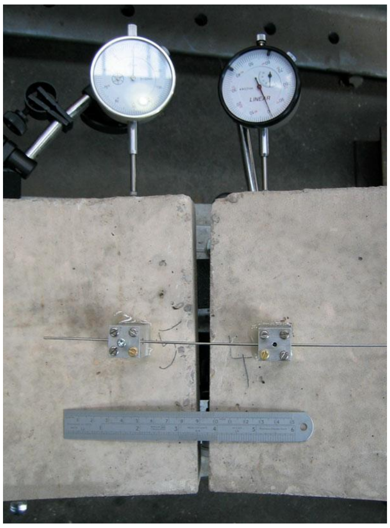

Figure 4 Cantilever containing MCF attached to tunnel lining.

## 4. EXPERIMENTAL RESULTS

The optical interrogation system is illustrated in figure 5. A tunable laser sweeps from 1550 to 1564 nm at 3.5 nm $s^{-1}$. This light is split into 4 channels via a network of couplers and circulators and coupled into the MCF using a fan-out. The fan-out uses HF etched single core fibres to couple light into each core of the MCF individually, we have previously described this fan-out elsewhere[6]. The light reflected by the FBG's is coupled into 4 separate photodetectors via the fanout and splitter network. In this way the four cores are sampled simultaneously. The effective grating wavelengths are determined by centroid fitting of data that fall within the FWHM of each grating spectrum. In this way the separation between pairs of gratings could be determined to ~1 pm.

The experiment consisted of moving one tunnel section relative to the adjacent section and recording the new grating spectra. The movement was independently measured using dial-gauge micrometers (0.02 mm resolution). Experimental results for the wavelength separation between a pair of gratings are shown in figure 6 as a function of the applied displacement. In this case we are able to observe displacements of the order of ±0.1 mm using the multicore cantilever system. Further sensitivity improvements could be realised by averaging over many measurements whilst still maintaining nominally realtime measurements with acquisition times over a few minutes.

## 5. DISCUSSION

In this experiment we have demonstrated two FBG's per fibre core, but there is no reason why this cannot be extended to 10's of FBG's per core, thus enabling several such displacement sensors to be interrogated using a single multicore fibre. Further improvements in sensitivity may be afforded by improved interrogation or data processing, and by better control of the location of the FBG's on the cantilever. Sensitivity can be maximised by ensuring that the gratings are close to the mounting points i.e. at the point of greatest curvature as shown in figure 3.

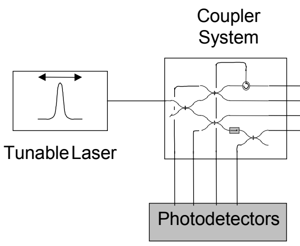

Figure 5 Optical interrogation system capable of making simultaneous reflection measurement from all four cores independently.

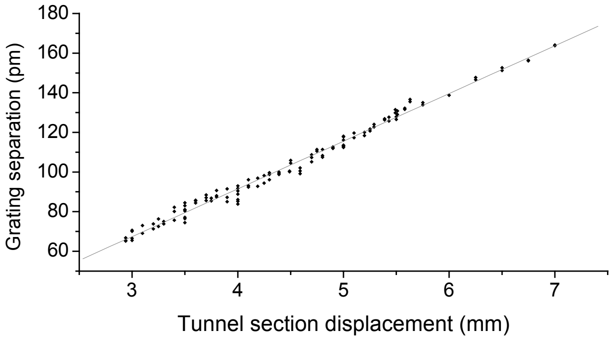

Figure 6 Experimental results from translation tests.

## 6. CONCLUSIONS

We have demonstrated the first example of a wavelength multiplexed sensor array in multicore fibre. Two measurement points are described in this work, but using standard FBG multiplexing techniques expansion up to 10's of measurement points is feasible. The sensors have been used to measure the shape of a simple cantilever, which in turn is used to monitor the relative displacement of concrete tunnel lining sections. Our sensor demonstrated a measurement resolution of ±0.1mm, which is deemed suitable for this application.

## ACKNOWLEDGEMENTS

W MacPherson would like to acknowledge the UK Engineering and Physical Science Research Council (EPSRC) for provision of funding via the Advanced Fellowship Programme and UK Defence Science and Technology Laboratory (Dstl) for provision of funding through the Joint Grant Scheme. The authors also wish to thank Dr. G. Fleming (NASA Langley) for supply of the multicore fibre.

## REFERENCES

1 M.L. Cooper, D.N. Chapman, C.D.F. Rogers and A.H.C. Chan, “Movements of the Piccadilly Line tunnels due to the Heathrow Express construction”, Geotechnique, **52**, No.4, p. 243-257, 2002.

2 A.D. Kersey, “A review of recent developments in fiber optic sensor technology”, Optical Fiber Tech., **2**, pp. 291-317, 1996.

3 C.J. Groves-Kirkby, “Optical-fibre strain sensing for structural health and load monitoring”, GEC Journal OF Tech., **15** (1), pp. 16-26, 1998.

4 E. Udd, S. Calvert, and M. Kunzler, “Usage of Fiber Grating Sensors to Perform Critical Measurements of Civil Infrastructure”, Proceedings of OFS-16, Nara, Japan, p. 496, 2003.

5 M. Song, S.B. Lee, S.S Choi, B. Lee, “Simultaneous measurement of temperature and Strain using two fibre bragg gratings embedded in a glass tube”, Opt. Fiber Technol. **3**, pp. 194-196, 1997.

6 G. M. H. Flockhart, W. N. MacPherson, J. S. Barton, J. D. C. Jones, L. Zhang, I. Bennion , “Two-axis bend measurement with Bragg gratings in multicore optical fiber”, Optics Letters, **28** (6), 387-389, 2003.

7 K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson, and J. Albert, “Bragg gratings fabricated in monomode photosensitive optical fibre by UV exposure through a phase mask”, Appl. Phys. Lett., **62**, pp. 1035-1037, 1993.

8 M.J. Gander, W.N. MacPherson, R. McBride, J.D.C. Jones, L. Zhang, I. Bennion, P.M. Blanchard, J.G. Burnett, and A.H. Greenaway, “Bend measurement using Bragg gratings in multicore fibre”, Elec. Lett., **Vol. 36**, No. 2, pp. 120-121, 2000.

9 J.M. Gere and S.P. Timoshenko, *Mechanics of Materials*, pub. Brooks Cole, 2002