Sensor Network for Structural Strain and High Hydraulic Pressure, Using Optical Fiber Grating Pairs, Interrogated in the Coherence Domain

J.P. Dakin, V. Foufelle, S.J. Russell, O Hadeler
Optoelectronics Research Centre, University of Southampton, SO17 1BJ, United Kingdom

W. Ecke, E. Geinitz, J. Schauer, R. Willsch
Institute for Physical High Technology (IPHT Jena), Helmholtzweg 4, D-07743 Jena, Germany

Abstract
This paper reports on progress with the coherence-domain method for interrogation of Bragg grating pairs, presenting for the first time a simple theoretical analysis of the interrogation procedure and describing the first measurements of useful engineering parameters (strain, pressure) with the system.

Introduction
We have recently reported a new coherence-domain multiplexing method for interrogating an array of matched Bragg grating pairs in a single fiber network [1]. Many previous methods have been devised for monitoring in-fiber Bragg gratings, including scanned filters (e.g., Fabry-Perot [2], acousto-optic [3], and stretched-fiber grating [4] passive filters using wavelength selective couplers [5], readout spectrometers [6,7] and stretched-fiber interferometers [8]). The passive wavelength-selective filters and the acousto-optic tunable filters promise the fastest response, but the stretched-fiber interferometer has demonstrated the greatest measurement precision. The latter can also be used in principle to read arrays of gratings using Fourier transform spectrometry [9], but this usually requires significant processing time and, in order to avoid distortions, a good quality signal, free of polarization fading. Unlike our present method, it requires all the gratings to have different wavelengths, limiting the number possible within the source linewidth.
Coherence multiplexing [10] has been used to muliplex sensors. When illuminated by a broadband source of short coherence length, each interferometric sensor in a chain shows visible fringes only when interrogated with an interferometer having an optical path difference (OPD) closely matching that of the sensor. Our recently-reported method [1] uses a coherence multiplexing scheme, which allows a linear array of grating pairs to be interrogated by a scanned receiving interferometer. We report on progress with the latest version of our system, shown schematically below.

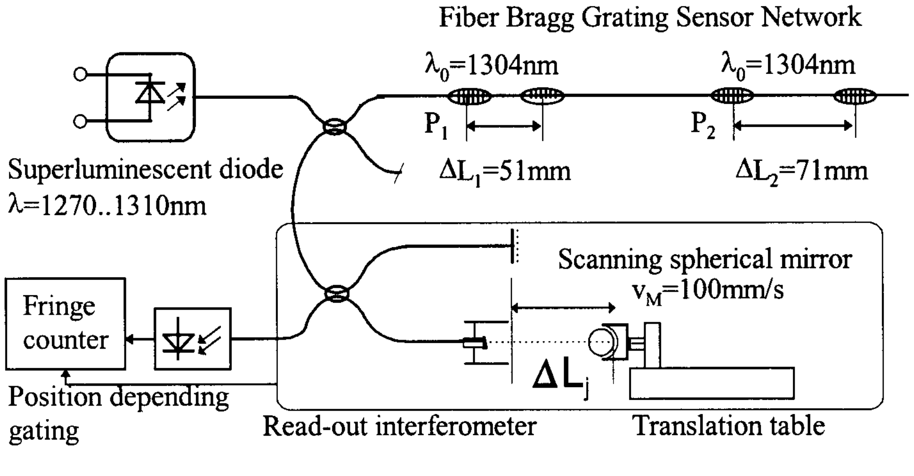

Fig. 1 Latest version of coherence-domain sensing system.

In this new system (Fig. 1) the read-out interferometer is now based on a precision computer-controlled linear translation table (Aerotech, type ALS

20020) and a superluminescent diode (SLD) with a smoother spectral output is used. As before, the sensing array consists of in-line matched grating pairs, with different spacings between each pair. As the table is scanned at constant velocity, a number of groups (bursts) of visible interference fringes are observed sequentially at points whenever the OPD of the scanned interferometer is close to the OPD of each grating pair (for simulated characteristic, see Fig. 2). A time-gated electronic counter measures the fringe-crossing rate during periods of high fringe contrast and a PC then determines, in turn, the centroid wavelength of each grating pair from this frequency. The greater travel of the new precision translator now enables all grating pairs to be interrogated in one sweep, unlike the earlier system, which used a much simpler push-pull solenoid translator. Using a simple low-finesse Fabry-Perot model, with mirror reflections matching that of the gratings, we have calculated the reflective spectrum of the grating pair. Then, with Mathcad 6.0, we have modelled the reflective spectrum to derive Fig. 2. As expected, this is a comb filter, with a peak reflection envelope of similar shape to that expected from just one of the initial gratings, Fig. 2. We are currently developing a more rigorous coupled-mode model, which we hope to publish is a future paper.

The Michelson interferometer acts as a second "raised cosine" filter. Maximum fringe amplitudes are observed when the period of the Michelson interferometer matches that of the Fabry-Perot formed by one of the grating pairs. A Mathcad simulation of the combined response of the scanned interrogation system is shown in Fig. 3

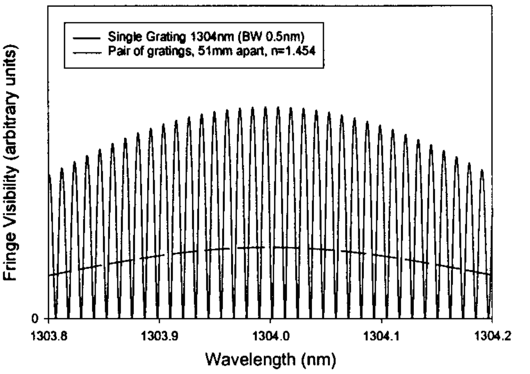

Fig. 2 Calculted reflective spectrum of an apodised Bragg grating pair, assuming a simple Fabry-Perot model

If the readout interferometer varies its pathlength linearly with time, i.e. at constant velocity v_M, then the fringe-crossing frequency has an approximately constant value, f_M, where $f_M=2v_M/\lambda_B$, and λ_B is the peak reflective wavelength of the grating pair.

The typical SLD spectrum is very broad, and if analyzed by a Michelson, only a few tens of fringes would normally be visible. Fortunately, the grating pairs act as a narrowband reflective filter, greatly increasing the coherence length of the light-source/grating-pair combination to approximately that of the length of the gratings, so many hundreds of fringes are observed in each burst, allowing more accurate frequency determination. In order to avoid undesirable overlap of observed fringes from different pairs of gratings, the spacings of each pair must differ by a decoherence length, substantially more than the coherence length corresponding to this reduced spectral width. In order to avoid crosstalk, broadband light sources with very few narrow-mode spectral features, or superluminescent fiber sources must be used, as otherwise these narrowband components will extend the

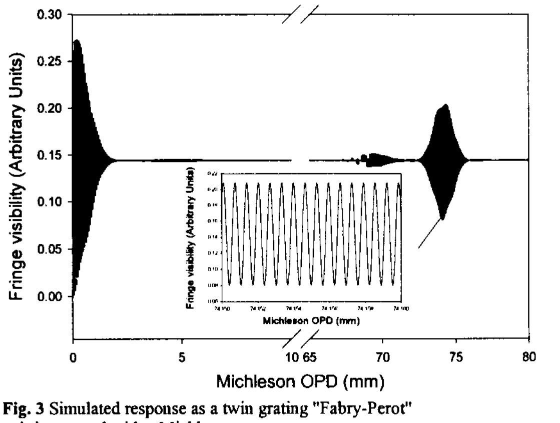

Fig. 3 Simulated response as a twin grating "Fabry-Perot" pair is scanned with a Michleson

decoherence length.

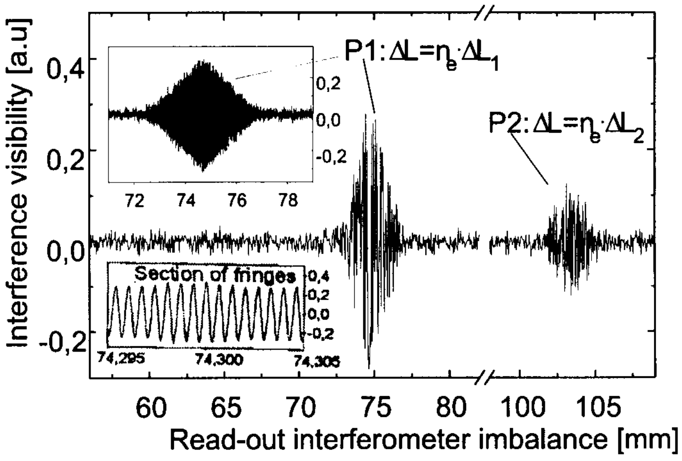

Fig. 4 Interference fringes of fibre Bragg grating pairs as a function of read-out interferometer imbalance (diagram disturbed by undersampling of full fringe pattern)

Experimental results

The multiplexing scheme has been tested experimentally with the arrangement of Fig. 1, using a 1290nm fiber-pigtailed SLD (Superlum SLD561) and a 0.7MΩ transimpedance receiver PRM56/4. The new SLD used in this latest work had a smooth intensity spectrum, essentially free of undesirable Fabry-Perot modes, which extended the coherence during earlier work. For our series of tests, the Bragg grating strain sensor array consisted of two fiber grating pairs P_1 and P_2 , each grating of 4mm length, ≈ 4.5 % reflectivity, mean wavelength λ_{B0}=1304nm, half-power spectral width $\delta\lambda$=0.5nm. The L_d of light from a Bragg grating of bandwidth $\delta\lambda$=0.5nm, was expected to be $4\cdot\lambda_{B0}^2/\delta\lambda$, i.e., approx. 14mm. This condition was full-filled by choosing the spacing between the P_1 grating pair to be L_1=51mm and, for P_2, the value of L_2=71mm. The fiber section between the grating pairs was set to be much longer, in our case to 0.7m.

The Michelson readout interferometer had a fixed-path fiber arm, with a silver-coated endface. The fiber endface in the variable path was angle polished, at 8° to avoid reflection and the lens-collimated light output was retro-reflected using a ball lens made from glass of refractive index n=2.0, with gold back coating. The spacing in the retro-reflecting arm was varied by the linear translation table, driven, under computer control, in alternating directions with a p-p amplitude L_M up to 120mm.

The mean velocity of the moving mirror was adjusted to $v_M=L_M/\delta t$= 0.1 m/s. The resulting mean frequency of interference signal was typically $f_M=2v_M/\lambda_{B0}$ =153kHz. When applying mechanical strain or pressure to a grating pair, small deviations $\delta\lambda_B$ occur from the initial value λ_{B0} leading to incremental frequency changes $\delta f_M=-(\delta\lambda_B/\lambda_{B0})\cdot f_M$. For noise reduction, the detected signal at frequency f_M was passed through a 150kHz filter of 20kHz pass-band and then to a counter. The frequency changes, δf_M, were determined by gating the counter during the mirror positions of maximum interference visibility.

A multiplexing scheme with two Bragg grating pairs was tested, firstly as a two-point strain sensor array and secondly where one of the sensors was used for hydraulic pressure sensing. For the first test, tensile strain was applied to the fiber leads of each grating pair in turn. At force levels F=0..2N, the strain-induced frequency change was -144Hz/N. From this value, a Bragg wavelength shift coefficient of 1.22nm/N was calculated, in

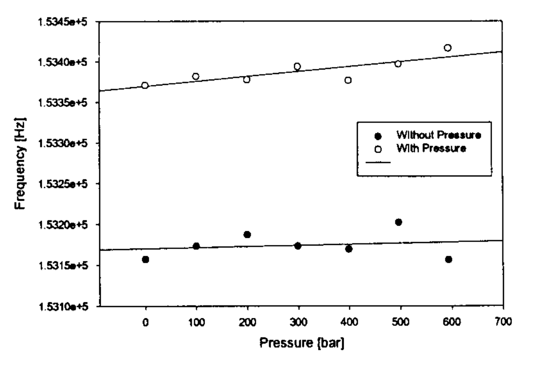

Fig. 5 Frequency characteristics of interference fringes of two grating pairs, with grating pair P1 under varying strain forces.

reasonable agreement with that of 1.17nm/N from direct spectral measurement [7]. By calculation, the equivalent temperature sensor would show a frequency shift of $-1.2 Hz \cdot K^{-1}$.
When one of the sensor pairs was reconfigured as a bare-fiber-grating pressure sensor [11], within a hydraulic pipe pressurized with oil, the measured scale factor was 0.6Hz/Mpa (see Fig. 5). It should be noted that pressure sensing using a bare grating is a particularly severe test of a wavelength interrogation scheme, because of the very small changes that occur even with high hydraulic pressures.

Conclusions

Significant improvements to our coherence-domain multiplexing scheme have been made and the new system has been experimentally tested. The scanning Michelson interferometer has been improved using a precision translator capable of scanning through all the grating pairs under computer control. The previously-reported problems of extended source coherence have been removed using an SLD device, with a spectral output free of mode-ripple. The system has been used for measuring strain as well as pressure influences of two multiplexed grating pairs.
The advantage of this coherence domain multiplexing scheme is that it needs no optical filters or fast pulsed optoelectronics, and can be combined with known wavelength and time domain multiplexing methods in order to increase the number of sensors possible in the network. No problems of polarization fading were observed in the laboratory system, but it is expected that if these occurred in a more severe environment, they could be alleviated using polarization scramblers in front of the interferometer [12] or Faraday mirrors in the Michelson interferometer [13].

References

1. J.P. Dakin, W. Ecke, M. Rothhardt, J. Schauer, K. Usbeck, R. Willsch, "New multiplexing scheme for monitoring fiber optic Bragg grating sensors in the coherence domain", Proc. of 12th Optical Fiber Sensor Conference, pp. 31-34 (1997)
2. A.D. Kersey, T.A. Berkoff, and W.W. Morey, "Multiplexed fiber Bragg grating strain-sensor system with a fiber Fabry-Perot wavelength filter", Optics Lett., Vol. **18**, pp. 1370-1372 (1993)
3. M.G. Xu, H. Geiger, J.-L. Archambault, L. Reekie, and J.P. Dakin, "Novel interrogating system forfibre Bragg grating sensors using an acousto-optic tunable filter", Electron. Lett., Vol. **29**, pp. 1510-1511 (1993)
4. D.A. Jackson, A.B. Lobo Ribeiro, L. Reekie, and J.-L. Archambault, "Simple multiplexing scheme for a fiber-optic grating sensor network", Optics Lett., Vol. **18**, pp. 1192-1194 (1993)
5. R.M. Measures, S. Melle, and K. Liu, "Wavelength demodulated Bragg grating fiber optic sensing systems for addressing smart structure critical issues", Smart Materials and Structures Vol. **1**, pp. 36-44 (1992)
6. C.G. Askins, M.A. Putnam, and E.J. Friebele, "Instrumentation for interrogating many-element fiber Bragg grating arrays", Smart Sensing, Processing and Instrumentation, Proc. SPIE Vol. **2444**, pp. 257-266 (1995)
7. W. Ecke, H. Bartelt, G. Schwotzer, K. Usbeck, R. Willsch, S. Birkle, T. Bosselmann, and P. Kraemmer, "Low-cost optical temperature and strain sensing networks using in-line fiber gratings", European Symposium on Lasers and Optics in Manufacturing, Munich 16-20 June 1997, Proc. SPIE Vol. **3099** (1997)
8. A.D. Kersey, T.A. Berkoff, and W.W. Morey, "High resolution fibre-grating based strain sensor with interferometric wavelength-shift detection", Electron. Lett. Vol. **28**, pp. 236-238 (1992)
9. M.A. Davis and A.D. Kersey, "Application of a fiber Fourier transform spectrometer to the detection of wavelength-encoded signals from Bragg grating sensors", J. of Lightwave Tech. Vol. **13**, pp. 1289-1295 (1995)
10. J.L. Brooks, R.H. Wetworth, R.C. Youngquist, M. Tur, B.Y. Kim, and H.J. Shaw, "Coherence multiplexing of fiber optic interferometric sensors", IEEE J. of Lightwave Tech. Vol. **3**, pp. 1062-1072 (1985)
11. M.G. Xu, L. Reekie, Y.T. Chow, and J.P. Dakin, "Optical in-fibre grating high pressure sensor", Electron.Lett. Vol. **29**, pp. 398-390 (1993)
12. A.D. Kersey, A. Dandridge, and M.J. Marrone, "Single-mode fiber pseudo-depolarizer", SPIE Vol. **838** Fiber Optic and Laser Sensors V, pp. 360-364 (1987)
13. A.D. Kersey, M.J. Marrone, M.A. Davis, "Polarisation insensitive fibre optic Michelson configuration", Electron. Lett. Vol. **27**, pp. 518-520 (1991)