

# Simple multiplexing scheme for a fiber-optic grating sensor network

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A new approach for the interrogation of a large number of fiber-optic grating sensors is proposed and demonstrated for a small number of sensors in which signal recovery is achieved by matching a receiving grating to its corresponding sensor. This technique is demonstrated for both quasi-static and periodic measurands, and the resolution achieved for a single sensor-receiving grating pair for quasi-static strain is  $4.12 \mu\epsilon$ .

Fiber-optic Bragg gratings<sup>1,2</sup> are attracting considerable interest for application as sensing elements in distributed sensors. As the grating sensors can be written point by point in series at any arbitrary location along a fiber without inducing any changes in the fiber dimensions, the sensitized fiber can be readily incorporated into complex structures,<sup>3</sup> such as composites, without compromising the structural integrity. In this type of application the gratings will be written at specific positions along the fiber such that when it is incorporated into the structure each sensing element will be located at a critical monitoring point.

For capital items such as passenger aircraft, a large number of sensors will be required. In order for one to interrogate and demultiplex the output signals from a serial array<sup>4,5</sup> of grating sensors, it is necessary that each sensor can be uniquely identified from the wavelength at which it has maximum reflectivity. This can be achieved in principle if each grating sensor has a specified working range  $\Delta\lambda_{1s}, \Delta\lambda_{2s}, \dots, \Delta\lambda_{ns}$ , where  $\Delta\lambda_{1s} = (\lambda_1 - \lambda_2)$ ,  $\Delta\lambda_{2s} = (\lambda_2 - \lambda_3)$ , and  $\Delta\lambda_{ns} = (\lambda_{n-1} - \lambda_n)$  and the instantaneous central reflecting wavelength of each grating sensor is within the specified range  $\Delta\lambda_{1s}, \Delta\lambda_{2s}, \dots, \Delta\lambda_{ns}$ , etc. If now the system is illuminated with a broadband source with a bandwidth  $\geq (\lambda_1 - \lambda_n)$ , then the backreflected signal will consist of  $(n - 1)$  frequency components, where the central wavelength of each component is directly related to the number of lines per millimeter of each grating reflector and hence to the current value of the measurand that it is designed to monitor.

Measurement of a large number of wavelengths with high precision is possible with costly instruments such as an optical spectrum analyzer; however, this is not feasible in a practical application owing to its size and weight and the frequent need to recalibrate the instrument. Recently an interrogation scheme based on a Mach-Zehnder interferometer acting as a wavelength discriminator was reported by Kersey *et al.*<sup>6</sup> This approach offers extremely high performance for a single sensor but is not easy to use

for multiplexing a large number of sensors without incorporating time-division multiplexing. Here we present a novel approach for multiplexing the output signals from a network of grating sensors, which permits virtually simultaneous interrogation of all the sensors, that is based on matching a receiving grating to a corresponding sensor.

The basic concept of the sensor-receiver grating pair is shown in Fig. 1. Light from the broadband source (BBS) is transferred to  $G_{1S}$ , the grating sensor, via the directional coupler; and light backreflected

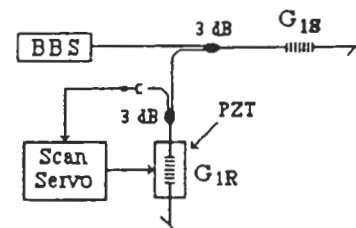


Fig. 1. Basic concept of the sensor-receiving grating pair.

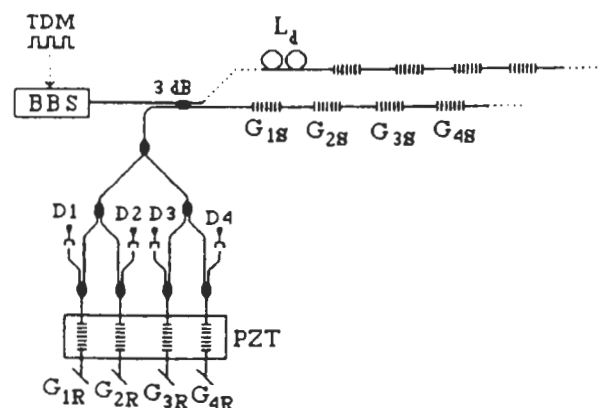


Fig. 2. Expansion of the arrangement shown in Fig. 1 to permit multiplexing of a large number of grating sensors. The number of sensors can be increased by incorporating additional sensing fibers with time-division multiplexing (TDM) (the source is then pulsed).

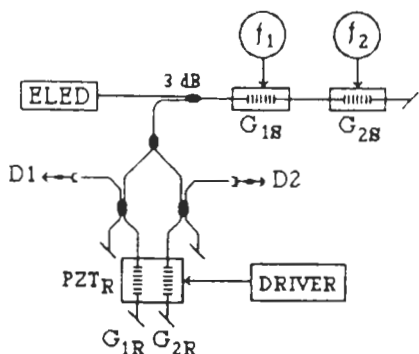


Fig. 3. Experimental system with two sensor-receiving grating pairs.

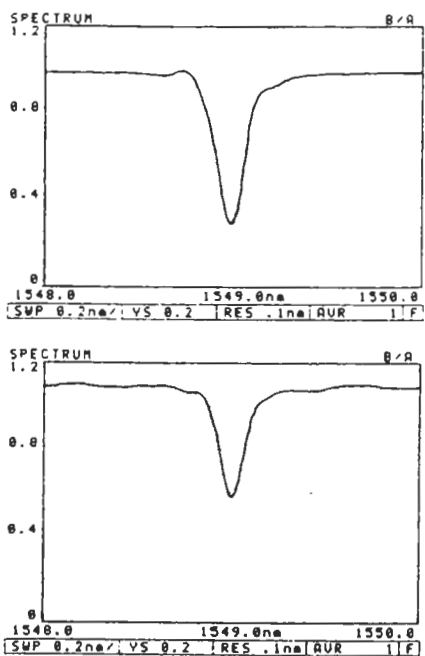


Fig. 4. Normalized transmission spectra of the grating pair  $G_1$  (top trace for  $G_{1S}$ , bottom trace for  $G_{1R}$ ).

from  $G_{1S}$  then propagates back through the fiber network to the receiving grating  $G_{1R}$ , which is mounted on a piezoelectric stretcher (PZT).  $G_{1R}$  is fabricated such that its central reflecting wavelength is identical to  $G_{1S}$  when both gratings are subject to the same stress. When  $G_{1S}$  is deployed as a sensor, its central reflecting wavelength will vary in direct proportion to the measurand and will generally not match that of  $G_{1R}$ . If now the central reflecting wavelength of  $G_{1R}$  is linearly swept over  $\Delta\lambda_{1S}$  by driving the PZT, then at one point in the sweep the reflecting wavelengths of  $G_{1S}$  and  $G_{1R}$  will exactly match, for in this condition a strong signal will be backreflected from  $G_{1R}$  and detected by the photodiode. Given that the voltage-to-wavelength coefficient of  $G_{1R}$  is known, the instantaneous value of the length of  $G_{1S}$  can be determined. This simple approach allows both the absolute length of  $G_{1S}$  and its variations to be determined. An alternative method of signal recovery, also indicated in Fig. 1, would be to use a closed-loop servo to maintain the matched condition. As shown in Fig. 2, it is straightforward to extend this arrangement to a

multiplexing topology. Here the receiving gratings are deployed in parallel, where the receiving gratings,  $G_{1R}$ ,  $G_{2R}$ ,  $G_{3R}$ , and  $G_{4R}$ , are individually matched to their corresponding sensing gratings,  $G_{1S}$ ,  $G_{2S}$ ,  $G_{3S}$ , and  $G_{4S}$ , when subject to identical stresses. The receiving gratings are now all mounted on the same PZT, which is driven linearly (or sinusoidally) such that all grating pairs will match once per cycle, permitting the lengths of  $G_{1S} \dots G_{4S}$  to be determined simultaneously at a high data rate. If a larger number of sensors is required, then several fibers with a similar number of sensors could be deployed with time-division multiplexing (TDM) used to interrogate sequentially each serial network of  $n$  sensors. The resolution of each grating-receiver pair depends critically on the linewidth of the gratings.

To demonstrate the feasibility of the multiplexing approach described above, we used a network of two sensor-receiving grating pairs. The experimental arrangement is shown in Fig. 3, in which the grating sensors  $G_{1S}$  and  $G_{2S}$  are mounted on separate PZT's and the receiving gratings  $G_{1R}$  and  $G_{2R}$  are mounted on the same PZT ( $PZT_R$ ). The resolutions of these PZT's were  $0.1 \mu\text{m/V}$ .

The network was illuminated with a  $1.55\text{-}\mu\text{m}$  edge-emitting light-emitting diode (ELED; Oki-506G) source with a bandwidth (FWHM) of 70 nm, and the launched power was  $\approx 10 \mu\text{W}$ . The grating pairs were formed in the fibers by exposing a short section

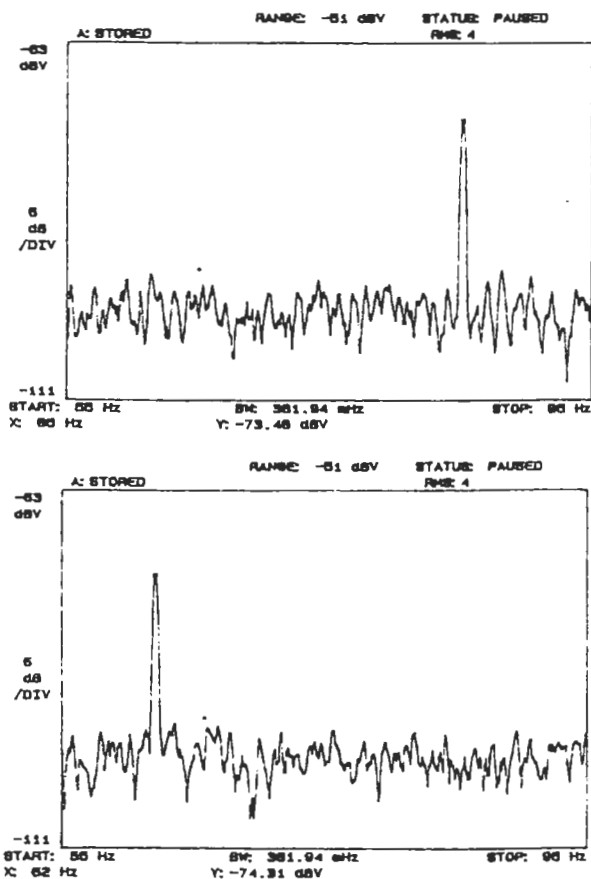


Fig. 5. Output spectra recorded as  $PZT_R$  is linearly swept when sensors  $G_{2S}$  (top trace) and  $G_{2S}$  (bottom trace) are driven at 85 and 62 Hz, respectively,

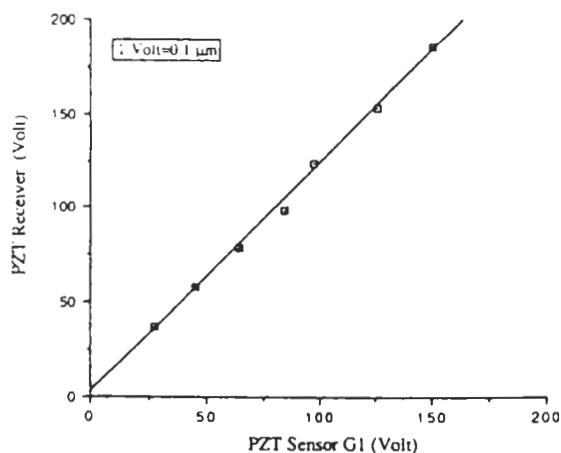


Fig. 6. Variation of matching voltage  $PZT_R$  as a function of the driving voltage applied to sensor  $G_{1S}$ .

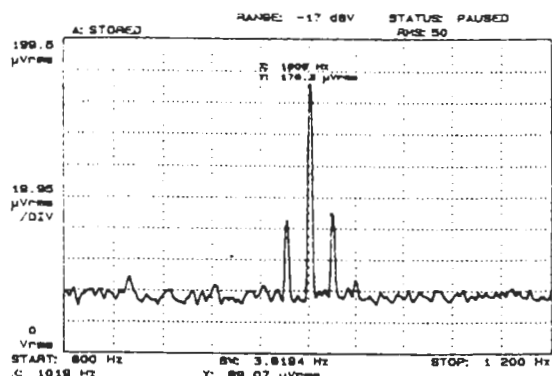


Fig. 7. Output spectrum from detector  $D_1$  when the sensor  $G_{1S}$  is subject to periodic strain (the intensity of the source is modulated at 1 kHz).

of the core, through the side of the fiber, to an interference pattern of intersecting coherent beams of UV light from an excimer laser.<sup>1</sup> This grating acts as a band-rejection filter, passing wavelengths that are not in resonance with the grating and strongly reflecting wavelengths that satisfy the Bragg condition.<sup>2</sup> In Fig. 4 we show one of the grating pair's transmission spectra normalized to the fiber transmission before the grating was manufactured. The Bragg wavelengths of the two grating pairs used in the experiment were  $1549.0 \pm 0.1$  and  $1534.8 \pm 0.1$  nm, with bandwidths of 0.2 nm.

In order to establish the multiplexing capability of the system, we modulated sensors  $G_{1S}$  and  $G_{2S}$  at frequencies of 62 and 85 Hz with an amplitude of  $875 \mu\epsilon$ . The amplified output signals from detectors  $D_1$  and  $D_2$  were coupled into separate channels of a spectrum analyzer, and the receiving grating pairs were swept over their respective ranges by driving  $PZT_R$  with a triangular voltage ramp; thus a signal at the sensor modulation frequency was generated only at the instant in time when the sensor-receiving grating pair was matched. The overall gain of each photodetector plus amplifier was  $17 \times 10^7$  V/W with a noise floor of  $26 \mu\text{V}/\sqrt{\text{Hz}}$ . The resulting output spectra are shown in Fig. 5; the signal-to-noise ratio for both sensors is  $\approx 25$  dB in

an  $\approx 0.4$ -Hz bandwidth, equivalent to a sensitivity of  $78 \mu\epsilon/\sqrt{\text{Hz}}$ . These spectra also show that there is no discernable cross talk between sensors.

We measured the linearity and resolution of the technique for quasi-static signals by varying the length of  $G_{1S}$ , by changing the voltage applied to  $PZT_{1S}$ , and by then adjusting the value of the voltage on  $PZT_R$  to maximize the output signal. These data are shown in Fig. 6, which as expected shows a linear relationship; the minimum detectable strain was  $4.16 \mu\epsilon$ . We determined the sensitivity by measuring the minimum induced strain necessary to destroy the matched condition. The system was also used to demonstrate the output of the grating sensors when they were driven with periodic signals, such that ac signal recovery could be used. As the input power was relatively low, these measurements were performed with the ELED amplitude modulated at 1 kHz. The results are shown in Fig. 7, in which the amplitudes of the sidebands at 1 kHz show that the grating sensor is being periodically strained at 20 Hz at an amplitude of  $594 \mu\epsilon$ . The signal-to-noise ratio (power in sidebands/noise) is 4.46 in a 3.82-Hz bandwidth, giving a sensitivity of  $68 \mu\epsilon/\sqrt{\text{Hz}}$ . The spectrum is that of a frequency-modulated carrier with a small modulation index.

In conclusion, a new multiplexing scheme has been proposed and demonstrated for Bragg grating sensors. The technique is demonstrated for both quasi-static and periodic measurands. The resolution achieved of  $4.12 \mu\epsilon$  was dictated by the linewidth of the grating; recently we produced gratings with a linewidth of  $5 \times 10^{-2}$  nm, which should improve the resolution to  $\approx 1 \mu\epsilon$ .

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## References

1. G. Meltz, W. W. Morey, and W. H. Glenn, *Opt. Lett.* **14**, 823 (1989).
2. W. W. Morey, G. Meltz, and W. H. Glenn, *Proc. Soc. Photo-Opt. Instrum. Eng.* **1169**, 98 (1989).
3. J. R. Dunphy, G. Meltz, F. P. Lamm, and W. W. Morey, *Proc. Soc. Photo-Opt. Instrum. Eng.* **1370**, 116 (1990).
4. W. W. Morey, in *Proceedings of Seventh Optical Fiber Sensors Conference* (Institution of Radio and Electronics Engineers Australia, Sydney, Australia, 1990), pp. 285-288.
5. W. W. Morey, J. R. Dunphy, and G. Meltz, *Proc. Soc. Photo-Opt. Instrum. Eng.* **1586**, 216 (1991).
6. A. D. Kersey, T. A. Berkoff, and W. W. Morey, in *Proceedings of First European Conference on Smart Structures and Materials* (Society of Photo-Optical Instrumentation Engineers, Bellingham, Wash., 1992), pp. 61-67.