Wavelength-division and spatial multiplexing using tandem interferometers for Bragg grating sensor networks

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We present a new method for the interrogation of large arrays of Bragg grating sensors. Eight gratings operating between the wavelengths of 1533 and 1555 nm have been demultiplexed. An unbalanced Mach–Zehnder interferometer illuminated by a single low-coherence source provides a high-phase-resolution output for each sensor, the outputs of which are sequentially selected in wavelength by a tunable Fabry–Perot interferometer. The minimum detectable strain measured was 90 $\mathrm{n}\varepsilon/\sqrt{\mathrm{Hz}}$ at 7 Hz for a wavelength of 1535 nm. © 1995 Optical Society of America

Considerable interest has been shown in Bragg grating sensors (BGS's) for monitoring strain in large-scale structures and as promising candidates for use as embedded fiber sensors in advanced composite materials for aerospace applications. The possibility that many gratings may be written into an optical fiber, creating a quasi-distributed serial sensing array, has called for flexible multiplexing schemes that are suitable for use with perhaps tens of sensors physically spaced at arbitrary points along the fiber length. A key issue with BGS's is the detection of the wavelength shift, for which high-resolution interferometric techniques have been demonstrated.[1,2] In this Letter we present a new system able to address a large number of BGS's and give high-resolution measurement of a perturbing field. The multiplexing scheme uses the inherent wavelength selectivity of the gratings (each grating may be written at a different wavelength) combined with the allocation of spatially distinct detection channels for a number of sensors, thus realizing a serial and/or a parallel multiplexing topology.

The sensors' operation is facilitated by two concatenated interferometers. The first interferometer, a Fabry–Perot (FP) interferometer, provides discrete wavelength tunability, spectrally slicing the output of the broadband source that illuminates the fiber network and permitting each of the BGS's to be illuminated sequentially. The transmission wavelength of the FP interferometer can be changed by piezoelectric tuning of the cavity spacing, with the FP passband limiting, in the current system, the operating range of the particular BGS selected. The second interferometer is an unbalanced fiber Mach–Zehnder interferometer that spectrally filters the light with a sinusoidal transfer function. If the Mach–Zehnder path imbalance is linearly increased by stretching one of the fiber arms, the peak output wavelengths are also linearly increased. This swept sinusoidal modulation, when convolved with the grating response, produces a periodic intensity modulation in the reflected light that generates, via the detector, an electrical carrier signal. When the grating is strained, its wavelength at peak reflectivity changes, resulting in a change in the phase of the electrical carrier. The application of periodic perturbations to the grating gives rise to sidebands around the carrier signal; for small-amplitude perturbations the sideband amplitudes respond linearly. The phase of the carrier and hence any signal applied to the grating may be recovered with a phase-locked loop or a lock-in amplifier, giving an output linearly proportional to the applied strain. An immediate advantage of wavelength tuning between sensors is that the physical spacing between individual gratings may be as short as desired, assuming that adjacent gratings reflect at different wavelengths. Additionally, the need for high-speed electrical signal processing, which is often required in time-division multiplexing, is removed. Thus a dense network of gratings may be inserted into a small or complex structure, such as the human body. Other wavelength-demultiplexing schemes using a single FP interferometer have been described,[2] but these approaches do not provide as high a resolution as our system, and some are unsuitable for recovering periodic measurands, having an inherently low bandwidth.

The experimental arrangement is shown in Fig. 1. The network was illuminated with an erbium-doped superfluorescent fiber source, producing approximately 100 μW of output power within a 30-nm bandwidth (1530–1560 nm). The fiber source was attached to a pigtailed Q filter (Queensgate Instruments Ltd. Model QF 100-40), which is a miniature FP cavity having a 39.5-nm free spectral range (FSR) and a bandwidth of 0.25 nm. The insertion loss of the filter was 2.7 dB. The spectrally filtered output was incident upon an unbalanced fiber Mach–Zehnder interferometer having an optical path difference (OPD) of 1.5 mm. One output leg of the Mach–Zehnder interferometer was fusion spliced to a 3-dB coupler, the output arms of which were spliced to another pair of 3-dB couplers. Four grating sensors were

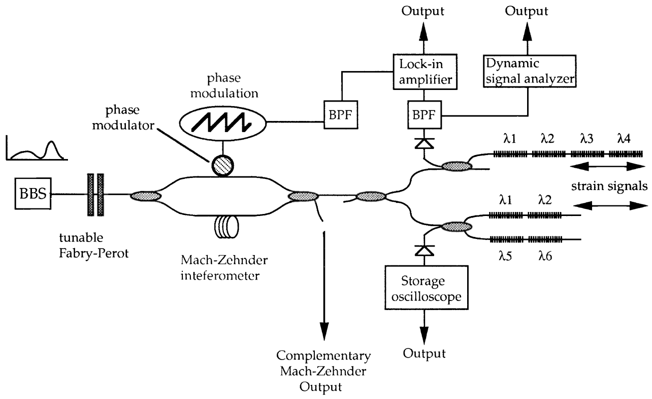

Fig. 1. BGS system: BBS, broadband source; BPF's, bandpass filters. The complementary output of the Mach–Zehnder interferometer could also be used to illuminate a similar network of gratings.

placed in line in the output arm of coupler 1, with each mounted on a separate piezoelectric element, allowing for a known dynamic strain signal to be applied to each sensor. A set of two in-line gratings was placed in both arms of coupler 2. The gratings had center wavelengths between 1533 and 1555 nm, peak power reflectivities of $\sim$50%, and spectral bandwidths (FWHM) of $\sim$0.2 nm. The transmission wavelength of the Q filter was sequentially tuned to each grating element by piezoelectric tuning of the cavity spacing, with a responsivity of $\sim$3.95 nm/V. Wavelength-division multiplexing was used to interrogate the gratings on both couplers, whereas spatial multiplexing (separate detectors) was used to distinguish between the couplers. The use of spatial multiplexing in this way can considerably increase the number of gratings that may be addressed, depending on the required signal-to-noise ratio.

A serrodyne modulation signal at a frequency of 130 Hz was applied to the Mach–Zehnder interferometer, producing a peak-to-peak phase excursion of 2π rad. The sensor signals were detected with two InGaAs photodiodes. The average optical power at each detector corresponded to $\sim$10 nW at 1535 nm, and the output fringe visibility from all the BGS's was $\sim$0.3.

From the Mach–Zehnder OPD the interferometer wavelength-to-phase-shift responsivity varied between 3.9 rad/nm at 1555 nm and 4 rad/nm at 1533 nm, depending on which sensor was selected. This resulted in strain-to-phase-shift responsivities of 4.485×10^{-3} and 4.544×10^{-3} rad/$\mu\varepsilon$, respectively, leading to maximum strain ranges of between ± 698 and $\pm 690\ \mu\varepsilon$.[2]

Initially the system was operated without the Q filter, and small-amplitude sinusoidal strain signals were applied to three of the four BGS's located in coupler 1 at frequencies of 7 Hz (1535 nm), 17 Hz (1549 nm), and 23 Hz (1555 nm), which appeared as sidebands around the carrier signal. The spectrum of the photodetector current is shown in Fig. 2(a). Figures 2(b) and 2(c) indicate how the presence of the Q filter allows for discrete wavelength selectivity as it is tuned to sensor 1 (1535 nm) and sensor 2 (1549 nm), respectively. We obtained an indication of the cross talk between channels by applying a large signal to one grating and measuring the signal overlap with the Q filter tuned to a different grating. No cross talk was observed, implying that the cross-talk level must be less than -33 dB, with the measurement limited by the detector noise floor. Using the FP transfer function, one may calculate the expected cross talk between two gratings when a peak in the transfer

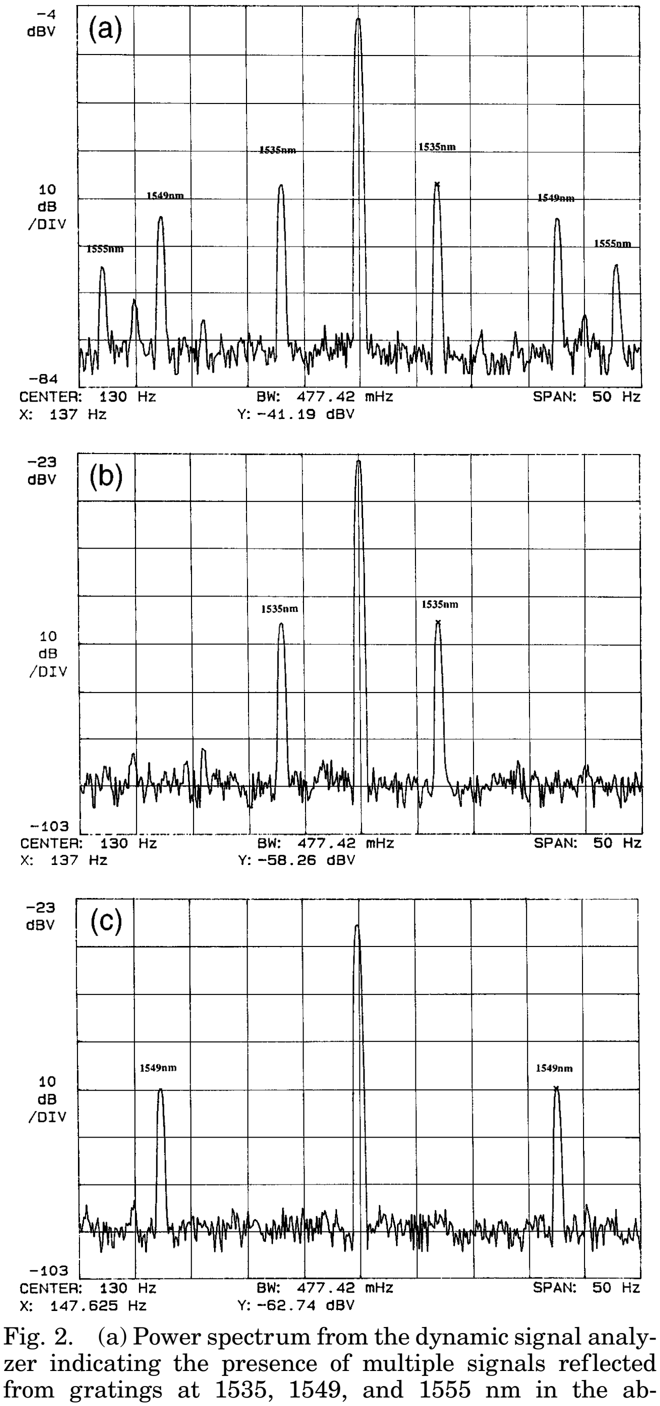

Fig. 2. (a) Power spectrum from the dynamic signal analyzer indicating the presence of multiple signals reflected from gratings at 1535, 1549, and 1555 nm in the absence of the Q filter and superimposed upon a 130-Hz carrier generated by the Mach–Zehnder interferometer. (b), (c) Spectra from the dynamic signal analyzer indicating how the presence of the Q filter allows for discrete wavelength selectivity as it is tuned to sensor 1 (1535 nm) and sensor 2 (1549 nm), respectively. Vertical scales, 10 dB/division; horizontal scales, 5 Hz/division.

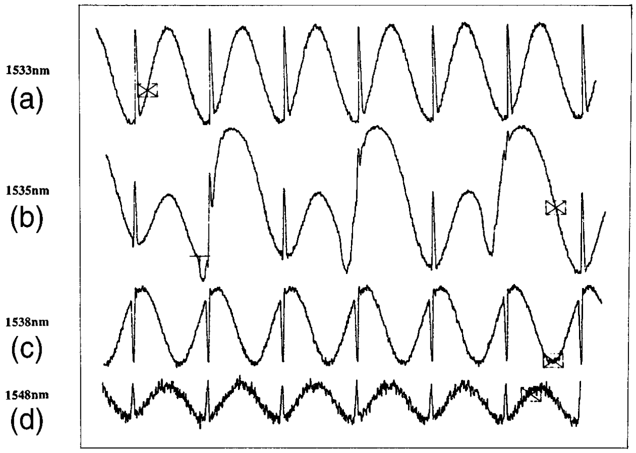

Fig. 3. Raw carrier signals recovered from the gratings located in the arms of coupler 2 operating at (a) 1533 nm, (b) 1535 nm, (c) 1538 nm, and (d) 1548 nm. A signal at 80 Hz was applied to the grating at 1535 nm.

function is centered on one of the gratings. Given a contrast for the Q filter of 80 dB (40 dB optical, manufacturer's data), the minimum level of cross talk between the two closest channels at 1533 and 1535 nm (assuming equal signal power in each) should be as low as −48 dB (−24 dB optical). This is consistent with the limit determined experimentally.

Figures 3(a), 3(b), 3(c), and 3(d) show the raw carrier signals recovered from the gratings located in the arms of coupler 2, operating at 1533, 1535, 1538, and 1548 nm, respectively, with a signal at 80 Hz applied to the grating at 1535 nm. The carrier strengths recovered from these gratings vary in accordance with the nonuniform intensity distribution of the superfluorescent fiber source, with the signal at 1535 nm coinciding with a peak in the gain curve.

To investigate the sensitivity of the system to small strain perturbations, we applied an rms strain of 3 $\mu\varepsilon$ at a frequency of 7 Hz to the BGS operating at 1535 nm. The photodetected output was bandpass filtered at the carrier modulation frequency and its phase was directly compared with the constant phase of the carrier signal with a lock-in amplifier, the output of which was recovered by the dynamic signal analyzer. From the signal analyzer, the signal-to-noise ratio was 31 dB in a 0.955-Hz bandwidth, which when normalized to a 1-Hz bandwidth corresponded to a minimum detectable strain perturbation of $\sim 90\ \text{n}\varepsilon/\sqrt{\text{Hz}}$ at 7 Hz. A similar measurement was made for the 1555-nm grating sensor that coincided with the low-output-power end of the superfluorescent fiber source; a minimum detectable strain of $\sim 240\ \text{n}\varepsilon/\sqrt{\text{Hz}}$ at 7 Hz was measured. Here we have demonstrated the system for dynamic strain, though incorporating a reference grating would permit the recovery of (high-resolution) quasi-static strain information.[3]

For absolute, unambiguous sensing of slowly varying measurands the maximum expected strain level applied to any BGS must be limited to one FSR of the Mach–Zehnder interferometer.[2] For example, the strain range, $R_{\text{M-Z}}$, limitation set by the Mach–Zehnder OPD is given by

$$R_{\text{M-Z}} = \frac{\lambda}{\xi \text{OPD}},$$

where λ is the wavelength of light from the grating and ξ is the normalized wavelength-to-strain shift responsivity of the grating. For a Mach–Zehnder OPD of 210 μm, equivalent to a FSR of 11.5 nm, the maximum strain range for a grating at 1.55 μm is ±5000 $\mu\varepsilon$. This imposes some restrictions on the properties of the FP interferometer. With the system as described here, there is a trade-off between the maximum operating range of the individual sensors, which should be less than the bandwidth of the FP interferometer, and the level of sensor cross talk. As the sensor range is increased by an increase in the FP bandwidth for a fixed FSR (thus reducing the finesse and the filter contrast), an increase appears in the level of cross talk between sensors. If a level of cross talk between sensors is specified as −40 dB electrical then the wavelength separation of sensors needs to be in the region of 5 nm, assuming a FP FSR of 100 nm (commercially available, as are electrical light-emitting diodes with 70-nm bandwidths at FWHM), allowing for 20 sensors—with the range of each sensor limited to ±500 $\mu\varepsilon$. To increase the operating range to ±5000 $\mu\varepsilon$, while maintaining a cross-talk level of −40 dB, one is limited to operating two BGS's per channel. Furthermore, in this system once the FP interferometer has been tuned to a grating it is a static filter, and nonlinearities can arise from the convolution of the FP passband with the reflection profile of the grating. These problems can be overcome by locking the FP interferometer to the peak of the grating reflectivity while the measurement is made. Some applications may require monitoring of both periodic and quasi-static strain, for example, monitoring vibration in an aircraft wing while keeping track of any long-term creep in the structure. If the resolution required for the quasi-static measurement is not too high, this information could be obtained directly by the FP interferometer,[2] with the periodic signal being obtained by the Mach–Zender interferometer. This approach would remove the need to lock the FP to the grating.

We have demonstrated the demodulation of eight BGS's by using a novel demultiplexing/interrogation scheme incorporating tandem interferometers combined with spatial multiplexing, allowing for static and dynamic phase measurement.

References

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