Pseudoheterodyne Demodulation Technique for Fiber Bragg Grating Sensors Using Two Matched Gratings

L. A. Ferreira, J. L. Santos, and F. Farahi

***Abstract*—A pseudoheterodyne, open-loop demodulation technique for detecting wavelength shifts in wavelength encoded fiber Bragg grating sensors is presented. The scheme uses a processing Bragg grating that is identical to one used as a sensor. When the processing fiber grating is stretched periodically, the system of two gratings produces a carrier at this frequency with its phase modulated by the measurand signal applied to the sensing grating. The demodulation technique is intrinsically immune to fluctuation of optical power in the system and is independent of the source spectral profile characteristics. A resolution of ≈ 1 $\mu\varepsilon/\sqrt{\text{Hz}}$ for static axial strain was achieved.**

***Index Terms*— Optical fibers.**

RECENTLY, a considerable research effort has been focused on fiber Bragg gratings (FBG's), particularly on systems using these devices for sensing applications [1]. The small size, good sensitivity and intrinsic nature of these devices, justify the interest in using them for monitoring structural integrity of buildings or fatigue loading of composite materials in advanced aerospace industry [2]. The signal obtained from a fiber Bragg grating sensor is encoded directly in wavelength domain which is, in general, an advantage over other sensing schemes and also facilitates wavelength division multiplexing [3]. However, for a practical system, the measurement of a small Bragg wavelength shift with conventional spectrometers or monochromators is not a good solution owing to their bulk-optical nature, size and lack of ruggedness and, in some cases, limited resolution. Several techniques have been developed for the demodulation of these sensors such as: interferometric detection [4], use of Fabry–Perot filters [5], wavelength matched grating pairs [6], [7], acoustooptic tunable filters [8] and laser–sensor combinations [9], which typically lead to high-resolution measurements. In a wide range of engineering applications, in order to reduce cost and complexity of the system, other demodulation schemes, with lower resolution, have been demonstrated using either a bulk or an all-fiber wavelength dependent filter [10], [11], or a highly overcoupled coupler (HOCC) [12].

Manuscript received July 30, 1996; revised October 15, 1996. The work of L. A. Ferreira was supported by the "Programa PRAXIS XXI." The work of F. Farahi was supported by the National Science Foundation under Grant DMI-9 413 966. This work was performed in part under the context of the EC Brite-Euram project NOSOST.

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Publisher Item Identifier S 1041-1135(97)02435-X.

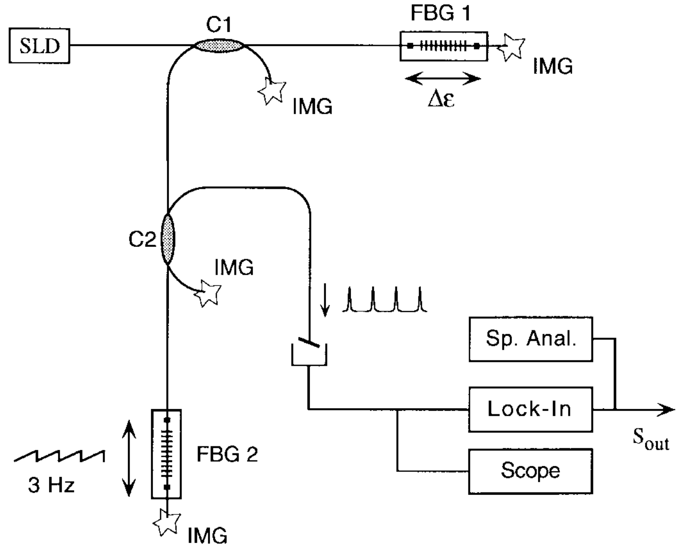
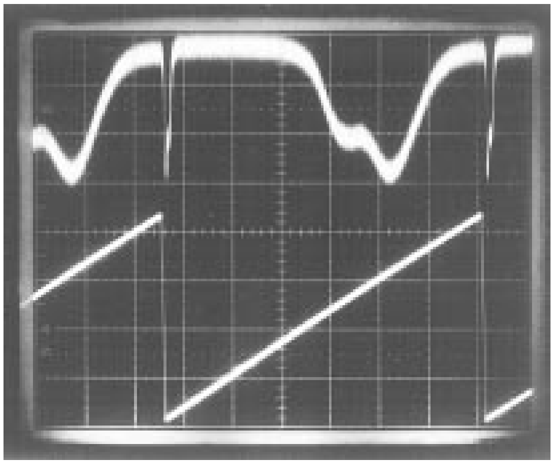


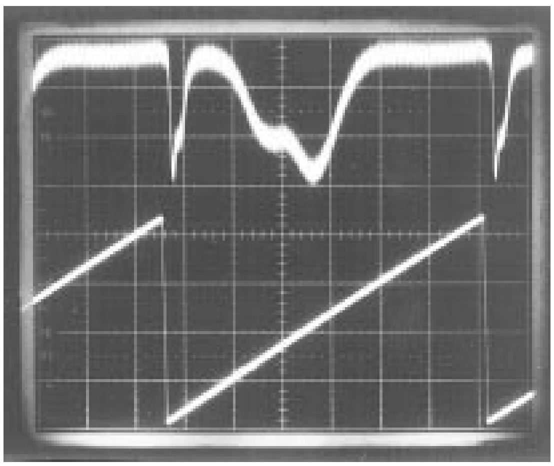
Fig. 1. Experimental set-up for Bragg wavelength shift detection (IMG: index matching gel).

Among all these schemes, the filter based technique which uses a second FBG for the interrogation of the signal from the sensor FBG has been pointed out as one of the most attractive techniques for demodulation of grating based sensing systems. With the second grating, it is possible to measure wavelength shifts in the sensing grating by tuning the maximum reflected optical power (reflective scheme [6]) or the minimum transmitted optical power (transmissive scheme [7]). These techniques are intrinsically of closed loop operation. In this letter, we present an open loop reflective matched grating demodulation scheme which works on the generation of a pseudoheterodyne carrier. The output signal is, therefore, a carrier with its phase proportional to the measurand applied to the sensing fiber Bragg grating. Besides its structural simplicity, the major advantage of this signal recovery scheme is its intrinsic immunity to optical power fluctuations in the system. It should also be addressed that this processing technique is not only inherently independent to variation in the power of the optical source and the loss in the system, it is also unaffected by possible fine structures superimposed on the source spectral profile envelope [13].

The system configuration used to demonstrate this signal recovery scheme is shown in Fig. 1. A pigtailed superluminescent source (Superlum SLD-361/A, $\lambda_{\text{peak}} = 826.7$ nm, $\Delta\lambda =$



(a)



(b)

Fig. 2. Detector output and ramp signal applied to the processing grating with: (a) strain applied to sensing fiber $= x$; (b) strain applied to sensing fiber $= x + 390\ \mu\varepsilon$.

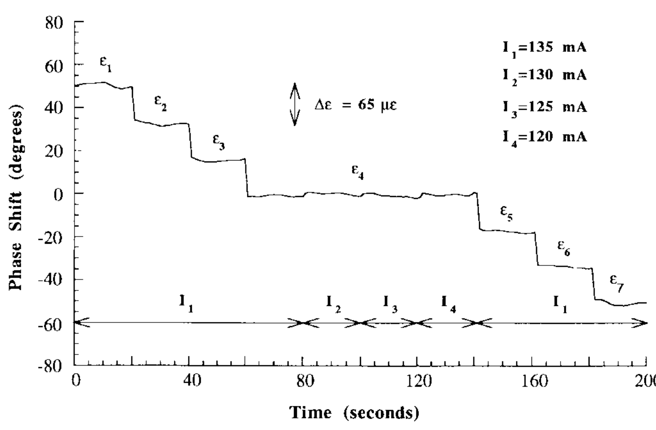


Fig. 3. Lock-in output: carrier phase shift for different values of strain applied to sensing fiber and also for different SLD injection current values.

20.2 nm, $P_{\text{in fiber}} = 0.55$ mW) was used to illuminate the system. The reflectivity of the sensing grating (FBG 1) and its spectral characteristics were measured at room temperature and with no axial strain applied to the fiber grating as: reflectivity ≈17%, $\lambda_B = 835.4$ nm, and $\delta\lambda \approx 0.2$ nm. The reflectivity of the processing grating, FBG 2, was 45% and care was taken during the fabrication process of this grating

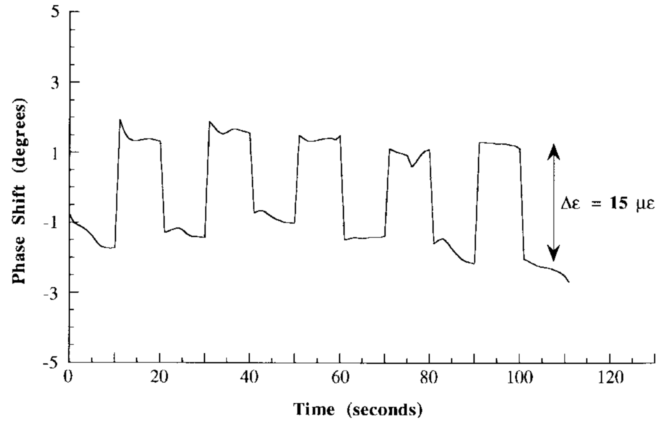


Fig. 4. Lock-in output: carrier phase shift for strain steps applied to sensing fiber.

to obtain similar spectral characteristics to those of FBG 1. The reflected light from the sensing grating was sent to the processing grating using a 3-dB coupler, C1. Light after being reflected again from the processing grating was detected by a photodiode using coupler C2. A sawtooth strain signal with a large amplitude (≈1.5 mε) at frequency of 3 Hz was applied to this grating to periodically match and mismatch the processing grating with respect to the sensing grating [Fig. 2(a)], generating a waveform with the same frequency as the sawtooth waveform. Slight structural mismatch between the sensing and processing grating is responsible for the visible structure of their convolution curve. Fig. 2(b) shows the photodiode signal, however, this time an axial strain of 390 $\mu\varepsilon$ was applied to the sensing grating. Comparison of these figures shows that signal of Fig. 2(b) is phase shifted with respect to the signal of Fig. 2(a). The phase change in this periodic signal, and, therefore, in the carrier obtained from it after bandpass filtering to recover the first harmonic, is caused by the strain applied to the sensing fiber. This phase can be measured when it is compared with the phase of a stable reference signal such as the first harmonic of the sawtooth wave. In our experiment, a lock-in amplifier was used for this purpose. Fig. 3 presents some of the obtained results, demonstrating that the signal recovery scheme is intrinsically immune to fluctuation of optical power in the system. The following steps were taken to obtain these results. The phase shift was recorded over a period of approximately 20 s for different values of applied axial strain to the sensing grating (FBG 1). Midway through the measurement, as the strain applied to the sensing fiber was kept constant, the injection current to SLD was varied over a range from 120 mA to 135 mA, that corresponds to ≈35% change in the optical power. As it can be observed from Fig. 3, the phase shift is unaffected by variation in optical power. Once again the current was kept constant and changes in phase were recorded by varying strain applied to the sensing fiber. Fig. 4 shows the signal at the output of lock-in amplifier when the response of system to a small periodic strain signal (amplitude strain of 15 $\mu\varepsilon$) was examined. Results of Fig. 5 were obtained for strain applied over a wide range. It is evident from this plot that, when this pseudoheterodyne recovery scheme is used, the phase shift of

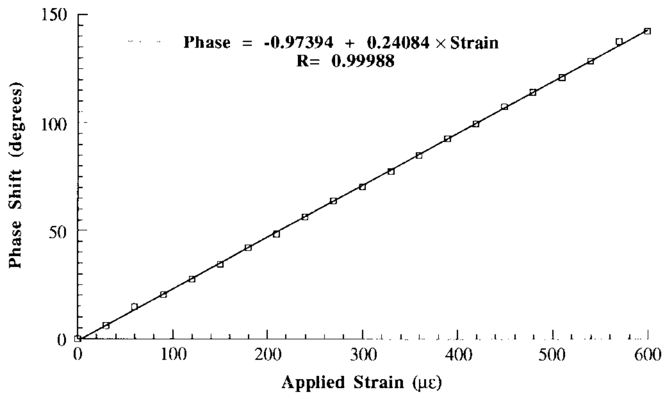


Fig. 5. Lock-in output: carrier phase shift versus applied strain to sensing fiber.

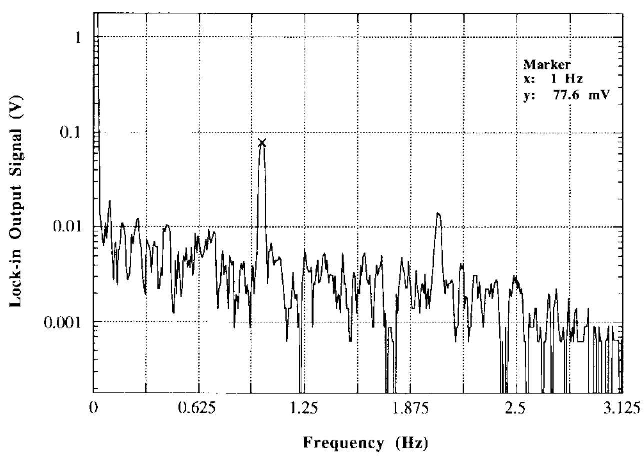


Fig. 6. Lock-in output signal for a low-frequency ac signal applied to sensing fiber.

the output signal is linearly dependent on the applied strain to the sensing fiber. The dc noise level was measured as being 10.7 mV/$\sqrt{\text{Hz}}$. Considering the slope of this plot, 0.24°/$\mu\varepsilon$, and the conversion factor of the lock-in amplifier, 18°/V, a static strain sensitivity of 0.8 $\mu\varepsilon/\sqrt{\text{Hz}}$ (0.5 pm/$\sqrt{\text{Hz}}$) was calculated. The sensitivity of the system was also measured by applying a low-frequency, 1 Hz, ac strain signal with an amplitude of 10.5 $\mu\varepsilon$ to FBG 1. The output signal from the lock-in amplifier was sent to a spectrum analyzer and two peaks corresponding to the first and second harmonics of the ac strain signal were observed (Fig. 6). A signal-to-noise ratio (SNR) of 30.7 dB in a bandwidth of 31 mHz was measured for the first harmonic. This corresponds to a strain sensitivity of 1.7 $\mu\varepsilon/\sqrt{\text{Hz}}$ (1.1 pm/$\sqrt{\text{Hz}}$). As expected, this is close to the value calculated using the data of Fig. 5. The resolution of the system should improve at higher frequencies, however this can only be demonstrated if a higher carrier frequency is generated. In our experiment, the processing grating was modulated with a piezoelectric translation stage that works efficiently only at very low frequencies. We are presently considering changes to increase the operation frequency of our experimental system.

As mentioned previously, the proposed demodulation scheme does not need any type of referentiation to system optical power fluctuations because it works on a phase measurement principle. The convolution curve of the two gratings can have a complex structure due to factors such as the mismatch between the reflectivity profiles of the two gratings, presence of ripple in the optical source or a combination of both, factors that will introduce higher harmonics in its Fourier expansion. However, after proper filtering, the first harmonic's phase can be selected, being its value relative to some reference phase is the important parameter, because it contains the information about the sensor status. Data presented above illustrates this characteristic. As mentioned, the mismatch between the spectral structures of the gratings (the sensing grating showed a spectral curve with two lobules) was responsible for the unusual shape of the convolution curve in Fig. 2. However, the obtained results are not affected by this feature, which goes in line with the above argument.

In conclusion, we have experimentally demonstrated the feasibility of a pseudoheterodyne recovery scheme for fiber Bragg grating sensors. The experimental results indicated a minimum detectable strain of ≈ 1 $\mu\varepsilon/\sqrt{\text{Hz}}$. The dynamic range of the sensing system is directly proportional to the amplitude of the scanning strain signal, and it was $\approx$80 dB in our experiments. The simplicity, ruggedness, small size, and immunity to optical power fluctuations are the main features of the sensing system utilising this demodulation scheme.

REFERENCES

[1] W. W. Morey, G. Meltz, and W. H. Glenn, "Fiber optic Bragg grating sensors," in *Proc. Soc. Photo-Opt. Instrum. Eng.*, vol. 1169, 1989, pp. 98–107.

[2] R. M. Measures, "Smart composite structures with embedded sensors," *Composites Eng.*, vol. 2, pp. 597–618, 1992.

[3] W. W. Morey, J. R. Dunphy, and G. Meltz, "Multiplexing fiber Bragg grating sensors," in *Proc. Soc. Photo-Opt. Instrum. Eng.*, vol. 1586, 1991, pp. 216–224.

[4] A. D. Kersey, T. A. Berkoff, and W. W. Morey, "High-resolution fiber-grating based strain sensor with interferometric wavelength-shift detection," *Electron. Lett.*, vol. 28, pp. 236–238, 1992.

[5] ——, "Fiber Fabry–Perot demodulation for Bragg grating strain-sensors," in *Proc. OFS'93*, Florence, Italy, 1993, pp. 39–42.

[6] D. A. Jackson, A. B. Lobo Ribeiro, L. Reekie, and J. -L. Archambault, "Simple multiplexing scheme for a fiber-optic grating sensor network," *Opt. Lett.*, vol. 18, pp. 1192–1194, 1993.

[7] M. A. Davis and A. D. Kersey, "Matched-filter interrogation technique for fiber Bragg grating array," *Electron. Lett.*, vol. 31, pp. 822–823, 1995.

[8] M. G. Xu, H. Geiger, J.-L. Archambault, L. Reekie, and J. P. Dakin, "Novel interrogating system for fiber Bragg grating sensors using an acousto-optic tunable filter," *Electron. Lett.*, vol. 29, pp. 1510–1511, 1993.

[9] A. D. Kersey, and W. W. Morey, "Multiplexed Bragg grating fiber-laser strain-sensor system with mode-locked interrogation," *Electron Lett.*, vol. 29, pp. 112–114, 1993.

[10] S. M. Melle, K. Liu, and R. M. Measures, "A passive wavelength demodulation system for guided-wave Bragg grating sensors," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 516–518, 1992.

[11] M. A. Davis and A. D. Kersey, "All-fiber Bragg grating strain-sensor demodulation technique using a wavelength division coupler," *Electron. Lett.*, vol. 30, pp. 75–77, 1994.

[12] Q. Zhang, D. A. Brown, H. Kung, J. E. Townsend, M. Chen, L. J. Reinhart, and T. F. Morse, "Use of highly overcoupled couplers to detect shifts in Bragg wavelength," *Electron. Lett.*, vol. 31, pp. 480–482, 1995.

[13] T. A. Berkoff, M. A. Davis, and A. D. Kersey, "Source structure induced measurement errors in fiber Bragg grating sensor arrays," in *Proc. Soc. Photo-Opt. Instrum. Eng.*, vol. 2294, 1994, pp. 60–68.