Multiplexed fiber Bragg grating strain-sensor system with a fiber Fabry–Perot wavelength filter

A. D. Kersey, T. A. Berkoff, and W. W. Morey*

Code 5674, Optical Sciences Division, Naval Research Laboratory, Washington, D.C. 20375

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The use of a fiber Fabry–Perot filter for detecting the wavelength shift of a fiber Bragg grating sensor or network of sensor elements along a common fiber path is described. Results obtained by using a system with four sensor elements are presented.

There has been considerable interest recently in the development of fiber-optic sensors based on in-fiber Bragg gratings (FBG’s), which can be written into Ge-doped fibers by use of a transverse holographic method. The use of such elements for distributed strain or temperature sensing in advanced composite or other structural elements and their use as in-line reflectors in interferometric systems has been discussed in several recent articles. One of the key issues we and others have addressed is related to the problem of detecting small shifts in the Bragg wavelength of FBG sensor elements; schemes based on simple broadband optical filtering, interferometric approaches, and fiber-laser approaches have been described. These approaches permit varying degrees of resolution and dynamic range and should be suitable to some of the application areas of interest for FBG sensors. In this Letter we describe results obtained with a fiber Fabry–Perot (FFP) filter as a demodulator for FBG sensors. The system can be operated either in a closed-loop tracking mode for use with a single sensor element or in a scanning mode for use with multiple sensors. In the latter case a derivative form of signal detection is used to permit higher resolution to strain-induced shifts in the Bragg wavelengths of the sensor elements.

Figure 1(a) shows the concept for a single FBG element. Light from a broadband source is input into the system, and the component reflected by the FBG is directed via a coupler to a tunable FFP filter, which has a bandwidth comparable with that of the FBG and a free spectral range (FSR) larger than with the operational wavelength domain of the FBG (typically less than ±5 nm). The narrow passband of the FFP filter is locked to the narrow-band FBG return signal, R, with a simple feedback-loop arrangement to the tuning mechanism of the FFP (e.g., with piezoelectric adjustment of the cavity spacing). To accomplish this, we modulate the transmission wavelength of the FFP slightly (~0.01 nm) by dithering the tuning elements at a frequency $f_d$. This results in a modulation in the optical output of the FFP, which, in general, will contain components at the fundamental and harmonics of $f_d$. When the wavelengths of the FBG return signal and FFP transmission peak are aligned, the amplitude of the fundamental is nulled. The amplitude of the modulation component at the fundamental of the dither frequency thus serves as an error signal that can be fed via a simple integrator circuit to the FFP tuning elements to lock the FFP passband wavelength to the Bragg wavelength, $\lambda_B$, of the sensor return signal. Consequently, the FFP control voltage (feedback voltage) is a measure of the mechanical or thermal perturbation of the FBG. One obvious limitation of this approach is that it can only be used to interrogate a single FBG, and multiplexing of the sensors is not possible in this locked mode.

Operating the FFP in a wavelength-scanning mode, however, provides a means for addressing several FBG elements. In this case, as shown in Fig. 1(b), several FBG sensor elements are placed along a fiber path (a star or branching system would be equally applicable). The nominal Bragg wavelengths and operational wavelength domains of the FBG’s are chosen not to overlap, and all fall within the spectral envelope of the source. Furthermore, the FSR

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Fig. 1. (a) Single FBG strain sensor with a FFP demodulator. (b) Multiplexed FBG array with a scanning FFP demodulator.
Fig. 2. (a) FFP transmission spectrum (arbitrarily centered at ~1542 nm). (b) Transmission spectrum of the 1548-nm FBG-sensor element. (Broadband input light.)

of the FFP is required to be greater than the total wavelength domain occupied by the sensors (i.e., $\lambda_1 \ldots \lambda_N$). The number of sensors that could be multiplexed with this approach clearly depends on the required operation wavelength domain ($\Delta \lambda_s$) of each FBG sensor, but, for example, for $\Delta \lambda_s$ of approximately ±3 nm (corresponding to an upper limit to the strain applied to the FPP of approximately ±2500 μstrain), six sensors could be addressed with a source of bandwidth ~36 nm (roughly that obtained with the broadband emission from an Er-doped fiber source). The light reflected from the FBG array is directed to the FFP, which is swept in wavelength by a control voltage used to adjust the mirror spacing. In this mode, the direct FBG sensor spectral returns, $R_1 \ldots R_N$, are obtained from the photodetector output, as would be observed with a conventional spectrometer. Typically, this gives limited resolution in terms of the minimum resolvable Bragg wavelength shift that can be detected. If the dither signal is maintained, however, and the photodetector signal is passed to an electrical mixer and low-pass filter arrangement that detects the component at the dither frequency, the derivative response to the spectral components in the array output is obtained. This produces a zero crossing at each of the FBG center wavelengths and provides for improved resolution in determining the Bragg wavelength shifts.

In the experimental demonstration of this approach, the source used was an Er-doped fiber superfluorescent source (BT&D EDFA 3000 amplifier), which comprised ~20 m of active fiber, the diode pump source, and a wavelength-division coupler. The FFP (Micron) had a ~43-nm FSR and a bandwidth of 0.38 nm (finesse ~110). The device provided for piezoelectric adjustment of the cavity spacing that tuned the transmission wavelength. A tuning responsivity of 1.3 nm/V was determined for the FFP device used. In the demonstration of the single-sensor system, a $\lambda_s = 1548$ nm FBG sensor with a ~0.2-nm bandwidth was used.

Figures 2(a) and 2(b) show the FFP and FBG transmission spectra, respectively. The FBG was surface attached to the underside of a steel plate 15 mm wide, 150 mm long, and 1.3 mm thick, which was subjected to three-point bending. A conventional resistive foil strain gauge was mounted beside the FBG element to provide a reference measurement of the strain. Light from the Er-doped fiber source was coupled through an isolator and a 3-dB coupler to the sensor element. The component of the light returned from the sensor available at the coupler was directed through the FFP. Operation of the FFP with a bias of ~20–30 V was preferable to prevent nonlinearities in piezoelectric response close to 0 V. A dither signal of ~100 mV at 500 Hz was applied to the FFP, although dither frequencies up to 20 kHz were possible. The feedback loop required for locking the FFP transmission to the Bragg wavelength of the sensor was configured with a lock-in amplifier for synchronous detection of the component at the dither frequency in the photodetector output.

Figure 3(a) shows the measured shift in the FFP feedback voltage and Bragg wavelength when the FBG mounting plate was subjected to three-point bending, inducing strains of as much as ~700 μstrain. As can be seen, the response was found to be linear with little scatter in the data. The uncertainty in the data of Fig. 3(a) was within the data points used in the plot. Figure 3(b) shows the output response to a low-frequency strain perturbation of 3-μstrain rms at 1 Hz. As can be seen from these results, a resolu-
tion in strain detectability of <0.3-μstrain rms was achieved with the 30-Hz measurement bandwidth used for these data.

Figure 4 shows the result obtained for a multiplexed arrangement of FBG elements with the FFP in the scanning mode. Here, FBG elements at Bragg wavelengths of 1538.6, 1544.2, and 1556.0 nm were added to the first element to produce a four-sensor array. In this mode of operation, the FFP was scanned over the wavelength range occupied by the four FBG sensors. The upper trace corresponds to the direct FFP output, whereas the lower trace is the derivative output provided by the dither component. The plot of Fig. 4 is a multioverlay of wavelength scans, with the strain applied to the nominally 1548.2-nm FBG adjusted in 100-μstrain increments from trace to trace. Closer examination of the shift in zero crossings of the derivative signal with applied strain indicated that a resolution of better than ±3 μstrain is possible in this case.

A technique for addressing FBG sensors based on an FFP filter has been described. The technique can be used in wavelength-tracking mode for addressing a single-sensor element or in a scanning mode for addressing an array of elements. Results demonstrating a strain resolution of <0.3-μstrain rms for a single sensor and better than ±3 μstrain with four FBG sensors along a single fiber have been presented.

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*Present address, United Technologies Research Center, East Hartford, Connecticut 06108.

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