Fiber Bragg Grating Array Sensor System Using a Bandpass Wavelength Division Multiplexer and Interferometric Detection

T. A. Berkoff and A. D. Kersey

Abstract—**A multiplexing approach for high-resolution sensing with Bragg gratings is described. The scheme uses a bandpass wavelength division multiplexer to separate the returned wavelengths from an array of gratings, and interferometric processing to attain high-strain resolution. A strain resolution of 1.5 nanostrain/$\sqrt{\text{Hz}}$ is demonstrated, with a sensor bandwidth of 10 Hz–2 kHz for four sensors.**

I. INTRODUCTION

FIBER Bragg grating (FBG) elements offer unique sensing capabilities for a variety of military, aerospace, and civil applications that can benefit from a distributed network of low-profile sensors. The ease of optically multiplexing a number of FBG elements along a single fiber path and the inherent wavelength encoding of sensor strain information makes these elements highly attractive for surface attachment or embedding into materials for structural monitoring purposes. Typically, recovery of strain information is accomplished by using optical instrumentation to convert the well-known strain-induced wavelength response of a FBG element to an output signal directly proportional to strain. Two-beam interferometric techniques can be used to detect small FBG wavelength shifts for this purpose [1] and have been shown to provide very high sensitivity. The multiplexed interrogation of an array of gratings using an interferometer has been previously demonstrated using time division multiplexing (TDM) [2]. Implementation of TDM, however, requires the use of a pulsed source, appropriate fiber lengths between sensor elements, and high-speed photo-detection and switching electronics that may be undesirable for some applications. Other approaches rely on wavelength multiplexing a number of FBG elements to recover information, such as using a scanning Fabry–Perot filter [3] or pair-matched grating detection [4], but typically these methods are limited in bandwidth and sensitivity when compared to detection schemes using an unbalanced two-beam interferometer. The recent development and availability of bandpass wavelength division multiplexers (BWDM), multichannel wavelength splitters, add-drop filters, and other components for the optical fiber communications field allow for the development and demonstration of new multiplexing and detection methods for FBG sensor arrays. In this letter, we report on the demonstration of a sensor system that uses an unbalanced interferometer and a commercially available BWDM to discriminate and detect strain signals from a wavelength multiplexed four element FBG array with high-strain resolution.

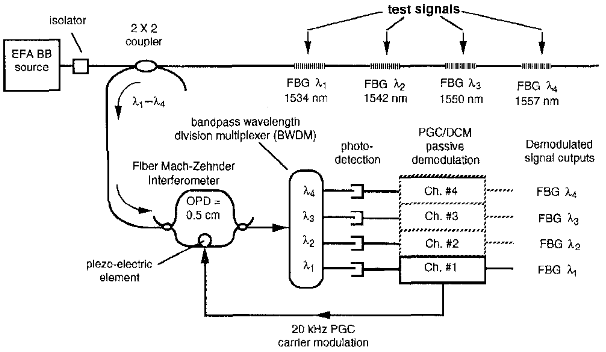

Fig. 1. Experimental system using a multiwavelength bandpass splitter and two-beam interferometer to recover strain information from a wavelength multiplexed FBG array.

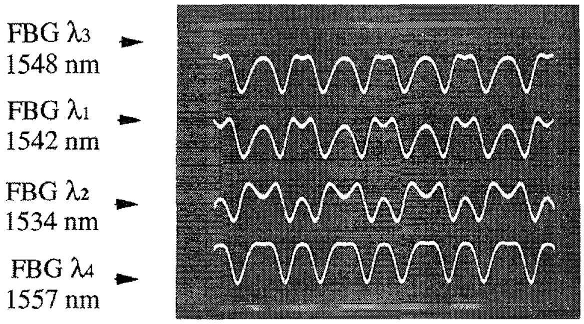

Fig. 2. Photodetected signals obtained for all four FBG sensors when a 20-kHz, 2.6-radian phase-shift carrier signal is applied to the interferometer.

II. PRINCIPLE OF OPERATION

In the interferometric interrogation approach, light from a broad-band source is used to illuminate the grating, and the reflected light is coupled to an unbalanced interferometer such as a Mach–Zehnder interferometer. The phase of the interferometer output depends on the grating wavelength, and a shift in grating wavelength due to strain $\Delta\varepsilon$ gives rise to a

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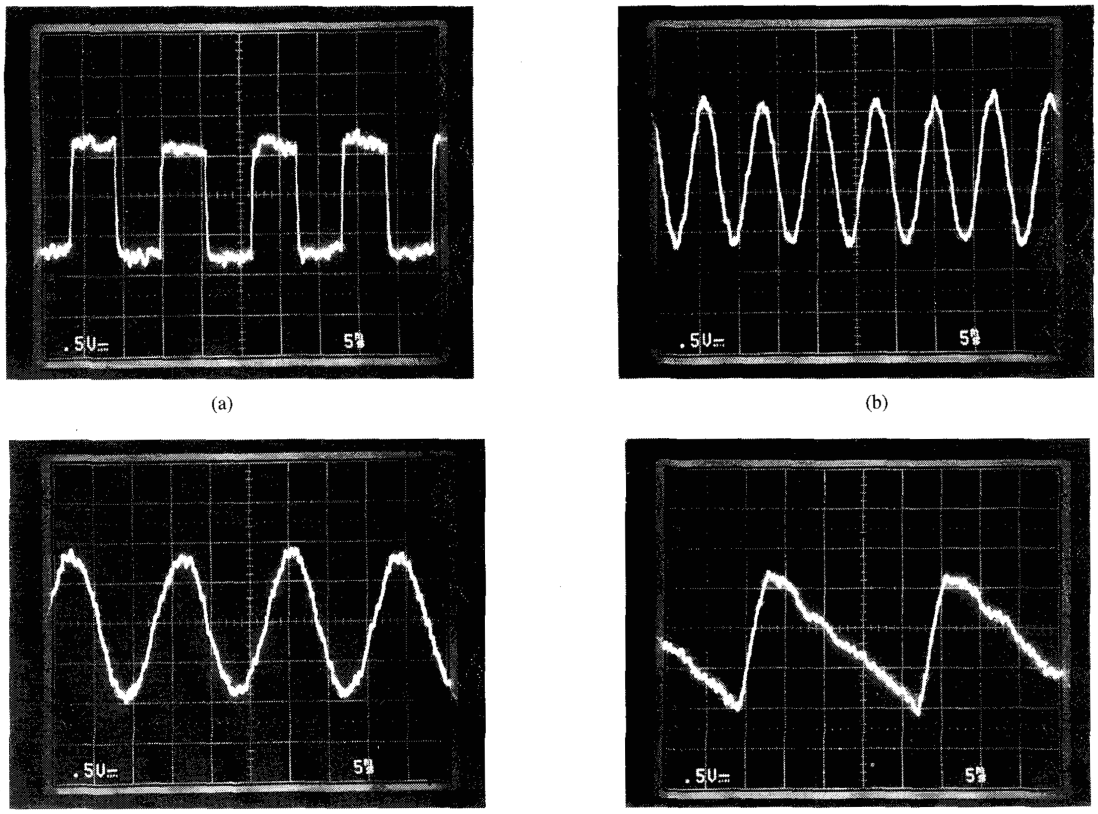

(a) (b)

(c) (d)

Fig. 3. Demodulated output signals obtained when a unique 1 5-strain pk test signal is simultaneously applied to each of the FBG elements. (a) FBGλ_1 (1534 nm): Square wave at 80 Hz. (b) FBGλ_4 (1557 nm): Sine wave at 130 Hz. (c) FBGλ_3 (1548 nm): Sine wave at 70 Hz. (d) FBGλ_2 (1542 nm): Asymmetric ramp at 45 Hz.

change in phase

$$\Delta\psi = -\frac{2\pi D}{\lambda_0^2}\,\xi\Delta\varepsilon$$

where D is the effective free-space optical path difference of the interferometer, λ_0 is the nominal wavelength of the FBG element, and ξ is the wavelength-strain response coefficient of the FBG element (typically ~1 nm/mε at $\lambda_0 = 1.3$ μm). In the approach presented here, a series of FBG elements at different nominal wavelengths forms a multiplexed array of sensors along a single fiber path. Consequently, the reflected signal consists of a series of spectral lines, that are passed through a path unbalanced Mach–Zehnder interferometer serving as a multispectral wavelength-shift detector to simultaneously transform the wavelength-encoded strain information from the FBG array signals into a series interferometric phase-dependent terms. Since the nominal wavelength terms do not interfere with each other, the intensity signal output from the interferometer is a composite signal from all the sensors in the array, represented by the simple summation

$$I = \sum_{m=1}^{n} a_m[1 + k_m \cos(\psi_m + \Delta\psi_m)]$$

where n is the total number of FBG elements, m is an integer value corresponding to a particular FBG element, a_m is a constant corresponding to the reflected FBG signal intensity and optical losses in the system, k_m is the effective interferometric visibility term attributed to the combination of the FBG signal coherence length and interferometer path imbalance, Ψ_m represents the static phase term due to the nominal wavelength of the mth grating, and $\Delta\Psi_m$ represents the time dependent dynamic phase shift due to strain perturbation applied to the mth grating. To demultiplex the spectral components of the composite signal, the output of the interferometer is coupled to a bandpass wavelength division multiplexer (BWDM), or other similar wavelength selective component, which separates the composite interferometer phase signal into discrete channels that correspond to a wavelength "window" about each of the FBG wavelengths in the array. Thus, each of the outputs of the wavelength splitter contains an interferometric signal that has a consinusoidal response to strain for a particular grating in the array. By modulating the phase of the interferometer, a phase-shift carrier signal can be generated on the photodetected outputs of the BWDM that allows for passive phase-shift demodulation using well-known electronic signal processing techniques such as synthetic heterodyne [5] or phase generated carrier modulation [6] to recover the phase-encoded strain information of interest.

III. EXPERIMENTAL DEMONSTRATION

To demonstrate this approach, the experimental system shown in Fig. 1 was assembled. A diode pumped Er-doped fiber superfluorescent source with an output power of ~1 mW

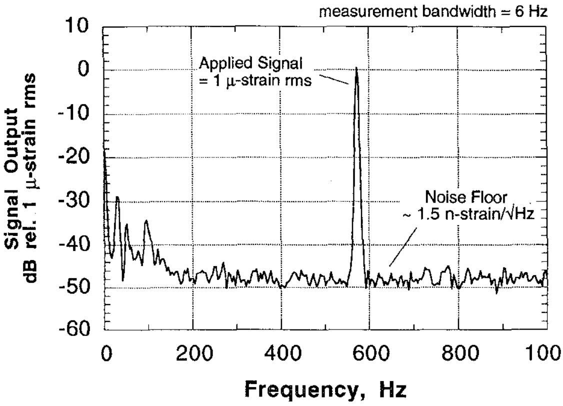

Fig. 4. Dynamic signal analyzer output corresponding to FBG 13 (1548 nm) when a 1-μ-strain rms, 575-Hz test signal was applied. The noise floor from 200–2000 Hz corresponds 1.5 nanostrain/$\sqrt{\text{Hz}}$.

and a 40-nm spectral bandwidth (1525–1565 nm) was used to illuminate a series of four FBG elements (FBG λ_1–λ_4) with nominal wavelengths at 1534 nm (λ_1), 1542 nm (λ_2), 1548 nm (λ_3), and 1557 nm (λ_4). Spectral width of the FBG elements were ~0.2 nm (FWHM) with reflectivities between 60–80%. The reflected optical signal from this array passed through a fiber Mach–Zehnder interferometer which was fabricated with a path imbalance of ~5 mm. The output port of the interferometer was coupled to the input of a four-channel BWDM manufactured by E-TEK. The spectral throughput of this device consisted of four wavelength bands with a spectral width of ~4 nm (FWHM) centered on the four different wavelengths of the FBG array. Each of the output leads from the BWDM was photodetected to obtain the desired interferometric sensor signals. A piezo-electric fiber stretcher in one of the Mach–Zehnder interferometer arms was used to induce a phase-shift carrier signal on the sensor output signals to enable passive recovery of dynamic phase-shift information using phase generated carrier (PGC) demodulation [6]. Fig. 2 shows the four photodetector signals when a 2.6 radian, 20 kHz carrier signal was applied to the interferometer, clearly showing the modulated consinusoidal phase-shift response for each of the FBG channels. To passively recover FBG strain information from the photodetector signals, a PGC demodulation circuit was used to process the phase-shift carrier signal, providing an output directly proportional to strain over a signal band from 10–2000 Hz. It should be noted that dynamic strain signals at even higher frequencies can be accommodated by increasing the frequency of the carrier signal used and by making appropriate changes to the PGC demodulation electronics.

The performance of the system was evaluated by applying test signals at known strain levels to each of the FBG elements in the array. The measured responsivity of the system was found to be 14 mrad/μ-strain, which is consistent with the predicted response for an interferometer with a path imbalance of 5 mm. Fig. 3 shows the fully demodulated sensor output signals obtained when each sensor in the system was subjected to a different 1-μ-strain pk test waveform. For this measurement, FBB λ_1 (1534 nm) was subjected to a square wave at 80 Hz, FBG λ_2 (1542 nm) was subjected to an asymmetric ramp at 45 Hz, FBG λ_3 (1548 nm) was subjected to sinusoid modulation at 70 Hz, and FBG λ_4 (1557 nm) was subjected to sinusoid modulation at 130 Hz. Although all four sensor signals could be simultaneously recovered using four separate PGC demodulation circuits, for this demonstration, a single PGC demodulation unit was sequentially connected to each of the photodetector outputs to recover the applied strain signals. Fig. 4 shows the recorded output obtained from a dynamic signal analyzer when a 1-μ-strain rms 575 Hz sinusoid test signal was applied to the 1548 nm FBG sensor. The noise floor from 200–2000 Hz was relatively flat, corresponding to a signal level of 1.5 nanostrain/$\sqrt{\text{Hz}}$. Similar noise performance was observed on the other FBG sensor channels. Evaluation of channel-to-channel crosstalk was accomplished by applying a sinusoid test signal to each of the FBG elements while recording the residual signal level that appeared on the other three FBG outputs. These measurements indicated that residual crosstalk signals in all cases were less than -53 dB, and more typically closer to -70 dB.

IV. CONCLUSION

In conclusion, we have reported on the experimental demonstration of a wavelength multiplexed fiber Bragg grating sensor system that uses a multiwavelength bandpass splitter and a path unbalanced two-beam interferometer to demultiplex and detect weak dynamic strain-induced wavelength shifts. Results obtained from a four-channel sensor system demonstrate high-resolution detection capability over a wide bandwidth and high-dynamic range. As multiwavelength passband splitters with a higher number of channels become commercially available, a larger number of FBG sensors can be addressed utilizing this technique.

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