Abstract—This paper describes a fiber Bragg grating strain sensor interrogation system based on a MEMS tunable Fabry-Perot filter. The shift in the Bragg wavelength due to strain applied to a sensor fiber is detected by means of a correlation algorithm which was implemented on an embedded digital signal processor. The instrument has a 70 nm tuning range, allowing multiple strain sensors to be multiplexed on the same fiber. The performance of the interrogator was characterized using an optical fiber containing 6 grating strain sensors embedded in a fiberglass test specimen. The measured RMS strain error was 1.5 microstrain, corresponding to a 1.2 pm RMS error in the estimated wavelength shift. Strain measurements are produced with an update rate of 39 samples/s.

Index Terms—Microelectromechanical devices, optical fiber transducers, strain measurement

I. INTRODUCTION

RAPID advances in optical microelectromechanical systems (MEMS) technology have occurred over the past decade, resulting in high-performance, compact optical components. Particular effort has been devoted to developing optical MEMS components for use in fiber optic telecommunication networks, such as tunable lasers [1], fiber optic switches [2], and tunable filters [3]. Similarly, a variety of fiber optic sensors have been developed by exploiting low-cost, high-performance optical components originally commercialized for telecommunication applications [4]. In particular, optical strain sensors based on fiber Bragg gratings (FBGs) have unique characteristics such as resistance to electromagnetic interference (EMI), multiplexing capability, and mechanical durability that make them attractive for a variety of industrial applications, including structural health monitoring [5, 6].

Optical fiber can be embedded into composite materials, allowing in-situ monitoring of the fabrication process or the detection of damage due to fatigue or impact [7, 8]. The simplest such sensors are used to detect longitudinal strain but transverse strain and strain gradients may be resolved through appropriate design of the sensor and interrogation scheme [9].

Here, we report on an instrument for interrogating FBG strain sensors based on a MEMS Fabry-Perot tunable filter. The small size, low power, and low voltage operation (< 25V) of this filter make it suitable for use in a compact interrogation unit such as the one recently demonstrated in [10]. In addition, the low insertion loss, wide tuning range, and fast response of the filter allow high resolution measurements of multiple sensors at fast sample rates. In the interrogation system described here, the filter is controlled using an embedded digital signal processor (DSP) which implements a correlation algorithm to identify the wavelength shift of each FBG sensor and provides real-time digital strain readings to an external PC using a serial interface.

II. INTERROGATION SYSTEM DESIGN

A block diagram of the interrogation system is shown in Fig. 1. A fiber-coupled superluminescent light emitting diode (SLED, InPhenix IPSDD1504) with a 1540 nm center wavelength (CWL) and 50 nm full-width at half-maximum (FWHM) emission bandwidth is used as a broadband light source. Light from the SLED passes through a three-port optical circulator and passes to a fiber that is instrumented with a number of FBG sensors. The FBG sensors have a narrowband reflection spectrum and longitudinal strain on an individual sensor induces a wavelength shift of 1.2 pm/µε in the reflection spectrum. Wavelength division multiplexing (WDM) is used to allow multiple FBG sensors to be detected on the same fiber; each FBG has a distinct CWL that is sufficiently separated in wavelength from adjacent sensors to allow the reflected light from individual sensors to be resolved. The interrogator was designed to allow a strain measurement span of ±2500 µε, requiring that at least a 6 nm separation between adjacent sensor CWLs. The reflected light from the sensors returns to the circulator, passes through the MEMS tunable filter, and is detected with a photodiode. A transimpedance amplifier converts the photocurrent into
voltage that is digitized with an A/D converter and processed using a DSP. The DSP measures the reflected light spectrum from the sensor fiber by using a D/A converter to generate the tuning voltage, sweeping the CWL of the MEMS tunable filter over the desired wavelength range.

A. MEMS Tunable Filter Characteristics

The MEMS tunable filter used here (Nortel MT-15) is a Fabry-Perot device, consisting of resonant optical cavity formed between a movable mirror supported by flexures above a fixed mirror on the device substrate [3]. A tuning voltage applied between the moving mirror and the substrate generates an electrostatic force that pulls the mirror downwards, reducing the cavity length and thereby reducing the CWL of the filter passband. The small size of the moving mirror results in fast mechanical response; the first resonance of this device has been measured to be 140 kHz [11].

The transmission characteristics of the tunable filter were measured with the SLED biased to achieve 2.5 mW total output power and with the tunable filter input fiber connected to port 2 of the circulator and the output fiber connected to an optical spectrum analyzer. The measured transmission characteristics of the filter along with the SLED emission spectrum are shown in Fig. 2(a). The total insertion loss, measured as the difference between the SLED output power density and the peak output power density from the filter, varies from 4.5 dB to 5.5 dB. When corrected for the insertion loss of the circulator (0.5 dB) and connector losses (1.0 dB), the MEMS filter insertion loss was found to vary from 3.0 dB to 4.0 dB over the measured tuning range. The specified tuning range for the filter is 70 nm with a maximum tuning voltage of 23 V. In our experiments, the tuning voltage was limited to 19 V and the measured tuning range spanned 1598 nm to 1540 nm. The measured tuning curve showing the filter CWL versus tuning voltage is plotted in Fig. 2(b). The filter bandwidth is nearly constant at 20 pm FWHM over the measured tuning range. The CWL depends quadratically on the tuning voltage as expected for an electrostatically-actuated device. As a result, the sensitivity of the CWL to the tuning voltage (which is equal to the slope of the tuning curve) increases approximately linearly with the tuning voltage, as shown in Fig. 2(c).

B. Demodulation Technique

A variety of methods have been devised to demodulate the FBG strain output. We used a correlation algorithm [12-14] in which the reflected spectrum from an unstrained grating is recorded and used as a reference spectrum. Strain measurements are then performed by calculating the cross-correlation between the reference spectrum and the spectrum of the grating under strain. Because the reference spectrum is recorded only once as part of an initialization routine, acquisition speed is not important and multiple averages are used to reduce the photodetector noise. In comparison to a simple peak-detection algorithm, the correlation algorithm greatly improves the signal-to-noise ratio (SNR) of the strain measurement.
measurement. Moreover, correlation calculations are readily performed at high speed on DSP hardware.

When the grating is strained, the reflection spectrum is wavelength shifted,
\[ r'(\lambda) = r(\lambda - \Delta \lambda), \] (1)

where \( r'(\lambda) \) is the spectrum of the strained grating, \( r(\lambda) \) is the reflection spectrum of the unstrained grating, and \( \Delta \lambda \) is the strain-induced wavelength shift. The spectrum is digitized by sampling the reflected light intensity at a number of discrete wavelengths spanning a wavelength range from \( \lambda_{\text{min}} \) to \( \lambda_{\text{max}} \).

\[ r(k) = r(\lambda_{\text{min}} + k \delta \lambda), \] (2)

where \( k \) is the sample index and \( \delta \lambda \) is the wavelength sampling resolution. The number of samples in each recorded spectrum is equal to the wavelength span divided by the resolution,
\[ N = (\lambda_{\text{max}} - \lambda_{\text{min}}) / \delta \lambda. \] (3)

The strain-induced wavelength shift \( \Delta \lambda \) is estimated by calculating the correlation \( c(m) \) between the digitized spectra \( r(k) \) and \( r'(k) \),
\[ c(k) = \sum_{m=0}^{N-1} r(m-k)r'(m) \] (4)

The sample index \( k_{\text{max}} \) corresponding to the maximum value of \( c(k) \) is used to estimate the wavelength shift, \( \Delta \lambda_e = k_{\text{max}} \delta \lambda \). Since the strain measurement is directly proportional to the wavelength shift, it is easy to see that the wavelength resolution \( \delta \lambda \) determines the resolution of the strain measurement, e.g. to resolve 1 \( \mu \)e, the spectrum must be sampled with a resolution of \( \delta \lambda = 1.2 \) pm. Assuming a constant wavelength span, \( \delta \lambda \) also determines the number of points used in the correlation calculation. Reducing \( \delta \lambda \) increases the number of samples and therefore increases the SNR in the correlation coefficients \( c(k) \). The correlation and peak-finding algorithms were simulated for an FBG with a Gaussian reflection spectrum, unity reflection amplitude, and a 0.27 nm FWHM. The RMS error in the estimated wavelength shift \( \Delta \lambda_e \) using each algorithm in the presence of Gaussian white noise added to the reflection spectrum is plotted in Fig. 3. Both algorithms were simulated using a fixed 0.4 nm wavelength span and \( N = 128, 256 \), and 512 samples. While the performance of each algorithm degrades with increasing noise, the RMS error in \( \Delta \lambda_e \) decreases with increasing \( N \) for the correlation algorithm. For \( N = 256 \) samples, the correlation algorithm reduces the RMS wavelength error by approximately an order of magnitude. Based on the simulation results, to achieve 1 \( \mu \)e RMS strain error (equivalent to 1.5 pm RMS wavelength error) an \( N = 256 \) sample correlation algorithm requires that the RMS noise in the reflection signal be 0.05 or less.

III. EXPERIMENTS AND RESULTS

A. Performance Characterization

Tests were performed using a fiber containing six FBG sensors (Micron Optics Inc.) with the first sensor CWL at 1548 nm and 6 nm spacing between subsequent CWLs. As shown in Fig. 2(a), the peak of the SLED emission spectrum was at 1540 nm, so the reflected intensity was greatest for the first sensor and diminished for subsequent sensors. The measured insertion loss from the SLED to the photodiode was 7 dB, a figure that included the FBG reflectivity, connector losses, and losses from the circulator and tunable filter. The photodiode current was converted into an output voltage using a transimpedance amplifier with a gain of \( 10^6 \) V/A. The narrow optical bandwidth of the tunable filter results in a small fraction of the input light intensity reaching the photodiode. With the SLED biased to produce 7.0 mW total output power and the tunable filter adjusted to the reflection peak of the first sensor the optical intensity on the photodiode was 0.59 \( \mu \)W, resulting in 0.53 V at the output of the transimpedance amplifier.

The dynamic performance of the optical system was initially characterized using a data acquisition card to generate the tuning voltage. A voltage ramp with a 20 V/ms slope was input to the tunable filter at a sample rate of 1 Msample/s, resulting in a sweep rate of approximately 0.1 nm/\( \mu \)s. Using this sweep rate, a reflection spectrum with a 41 nm wavelength span was recorded in 400 \( \mu \)s. The tuning voltage and the photodetector voltage were simultaneously digitized and stored using a digital oscilloscope. The wavelength corresponding to each photodetector voltage sample was computed using a 4th order polynomial fit to the tuning curve shown in Fig. 2(b). A plot of the photodetector voltage versus wavelength is shown in Fig. 4. The reflection peak corresponding to the first sensor, measured at a CWL of 1548 nm...
1548.6 nm, shows a linewidth of 0.26 nm FWHM, within the manufacturer’s specified range (0.27 ± 0.1 nm) for the FBG array. The amplitude of this peak was 0.53 V, 132.5 times larger than the photodetector RMS noise level of 4 mV, whereas the peak corresponding to the 6th sensor had an amplitude of 80 mV. The RMS noise level normalized to the amplitude of the smallest reflection peak is 0.05, sufficient to allow the CWL of this sensor to be detected with approximately 1.5 pm accuracy.

Fig. 4. Reflected intensity spectrum measured using the MEMS tunable filter and an optical fiber containing an array of 6 FBG sensors. The wavelength axis is plotted relative to the CWL of the first sensor (1548.6 nm). The full 30 nm scan was acquired in 0.3 ms. Inset: high resolution scan of the first sensor acquired at a scan speed of 0.1 nm/µs, showing 0.26 FWHM.

B. DSP Implementation

The correlation routine was implemented on a 150 MHz fixed-point 16-bit DSP (TI TMSF2812). The tuning voltage was generated using a 16-bit D/A converter controlled by the DSP through an SPI serial interface running at 10 MHz, allowing voltage updates at 625 ksamples/s. The tuning voltage resolution was 366 µV/LSB. The variation in tuning sensitivity over the wavelength range, shown in Fig 2(c), caused the wavelength resolution to vary over the tuning range. In our experiments, an array of FBGs was used in which the individual FBG CWLs ranged from 1548 nm to 1578 nm, resulting in a wavelength resolution from 2.2 pm/LSB to 1.2 pm/LSB, respectively. Due to relatively limited DSP memory, it was not possible to store high resolution spectra that spanned the entire tuning range. Instead, strain measurements were performed by collecting high resolution 1024 point spectra only in the immediate neighborhood of each FBG. For each FBG, strain measurements were performed as follows: (1) a coarse scan of the FBG spectrum was collected with a 16 LSB step size; (2) the peak in the coarse spectrum was identified; (3) a fine 1024-point scan was performed with a 1 LSB step size in the neighborhood of the reflectivity peak; (4) the correlation calculation was performed and the sample index corresponding to the peak correlation value was identified; (5) the sample index was converted into wavelength shift using a look-up-table constructed from a 4th-order polynomial fit to the tuning characteristic; and (6) the wavelength shift was converted into a strain reading. Correlation calculations were performed by correlating a 256 point reference spectrum with a 1024 point scan of each sensor. The noise performance of was the same as a 256 point correlation but allowed a wider span. The correlation calculation had a timed duration of 2.4 ms while the total time required to produce a single strain measurement was 25.4 ms. As implemented, the measurement time is dominated by the time to collect the 1024 point fine spectral scan, which was 16.8 ms. The fine scan included a 3 ms to allow the MEMS tunable filter to settle before performing the scan, and four samples of the photodetector voltage were averaged at each wavelength step to reduce noise. Assuming no reduction in the speed of the correlation calculations, we estimate that the strain from 6 gratings could be measured in approximately 15 ms if the wavelength scan duration could be improved to the 0.3 ms demonstrated in laboratory tests using PC-based data acquisition hardware.

A photograph of the interrogation system is shown in Fig. 5. The system was housed in a rack-mountable enclosure measuring 480 mm × 87 mm × 204 mm. The optical components, including the SLED and MEMS tunable filter were mounted on a printed circuit board (PCB) containing control electronics to regulate the SLED current and to control the thermoelectric coolers (TEC) on the SLED and MEMS filter. The DSP board was mounted beneath the optics PCB along with PCBs providing a pushbutton user interface and the RS232 serial interface.

Fig. 5. Interrogation system. Top: optics board. Bottom: Enclosure and control electronics.

C. Testing

A fiberglass test specimen was constructed and instrumented with an optical fiber containing an array of 6 FBG sensors. The specimen, measuring 0.4 inches thick, 8 inches wide and 30 inches long, was composed of 36 plies of
aerospace grade fiberglass laminate (Boeing Material Specification BMS8-79 CL3 7781). The optical fiber was embedded between layers 18 and 19 of the specimen. The 36-ply laminate was cured at a vacuum bag pressure of 10.8 psi and at 250°F using heat blankets. During the curing process, there was difficulty controlling the surface temperature of the specimen, which probably exceeded 300°F. The strain sensors in the embedded fiber suffered from greatly increased insertion loss, indicating damage during the process used to fabricate the test specimen. As a result, only three of the strain sensors could be detected in the specimen. A plot of the reflection spectrum from these three gratings measured with the SLED biased to produce 1 mW of total output power is shown in Fig. 6. The SLED was a different unit from the one used in earlier tests and had a peak output intensity at 1580 nm but was otherwise identical to the first unit. The RMS noise level measured as a fraction of the peak reflected intensity was 0.05 (sensor 1), 0.08 (sensor 2), and 0.15 (sensor 3). The unstrained CWLs for these sensors were 1578 nm, 1572 nm, and 1566 nm.

Fig. 6. Reflected spectrum from fiber embedded in test specimen. Three reflection peaks corresponding to the FBG sensors are visible.

The test specimen was mounted in a universal testing machine and loaded with tensile stress from 0 to 16000 psi in 500 psi increments, resulting in a maximum applied strain of approximately 2750 µε. Resistive strain gauges, mounted on the surface of the test specimen above each embedded grating, were used as reference measurements. The percentage difference between each FGB and the corresponding reference strain gauge versus applied strain is shown in Fig. 7. The worst-case difference was 22%, with a typical difference of less than 10%. The source of the difference in the strain readings between the surface-mounted resistive strain gauges and the embedded fiber sensors is not known; it is possible that some of the difference reflects a true difference in the strain experienced at the different sensor locations. The RMS strain fluctuation on the three sensors was 1.5 µε (sensor 1), 4 µε (sensor 2), and 6 µε (sensor 3), corresponding to RMS wavelength errors of 1.8 pm, 4.8 pm, and 7.2 pm. The experimental RMS wavelength errors are approximately a factor of two greater than the simulated values presented in Fig. 3(b) for the same photodetector RMS noise levels. This difference may be due to fact that the photodetector noise is not white and contains 1/√noise as well as interference from the switching power supply.

IV. CONCLUSION

The MEMS-based FBG interrogation system described here has a number of unique characteristics. The demonstrated scan speed of the tunable filter was 0.1 nm/µs, allowing the reflection spectrum from 6 FBGs spanning a 30 nm wavelength range to be measured in 0.3 ms. Although the maximum specified scan speed for this filter is 10 nm/µs, increasing the speed would likely require increasing the transimpedance amplifier bandwidth, resulting in increased noise and ultimately degrading the strain measurement accuracy. The 70 nm tuning range of the MEMS filter is sufficient to allow approximately 12 FBG sensors each having a ±2500 µε span to be interrogated. In a laboratory test, the SLED broadband light source provided sufficient intensity to allow high resolution measurements of all the sensors in a 6 sensor array. The RMS noise level (normalized to the FBG reflection peak) was 0.05 at the sensor whose CWL was farthest from the emission peak of the SLED, a noise level that is consistent with a 1.5 pm RMS wavelength resolution. When implemented on an embedded DSP, wavelength shift measurements were performed within 2.4 ms using a correlation algorithm, and a single strain reading was produced every 25.4 ms, with 150 ms required to measure the strain from 6 sensors. The DSP-based strain measurement time was dominated by the time required to acquire the 1024 point FBG reflection spectrum; a tenfold reduction in the measurement time could be achieved by increasing the scan speed to the 0.1 nm/µs demonstrated using PC-based data acquisition hardware.

REFERENCES


