Interrogation of fiber grating sensor arrays using a wavelength-swept fiber laser

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Abstract

We demonstrate a novel application of a wavelength-swept fiber laser to fiber Bragg grating sensor array interrogation. The laser provides high signal powers of >3 mW with <0.1 nm spectral resolution over 28 nm wavelength span. Using time interval counting, we demonstrate static/dynamic strain measurements with a resolution of 0.47 $\mu\varepsilon$ rms at a sampling rate of 250 Hz.

Fiber-optic sensor arrays based on fiber Bragg gratings have been a major topic of recent research in the area of quasi-distributed sensing.[1-9] In most of these sensor systems the absolute magnitude of environmental perturbations experienced by individually identifiable gratings, or sub-systems of gratings, are determined from the induced changes in the individual grating Bragg wavelengths. Various interrogation schemes have been demonstrated for the detection of the small Bragg wavelength shifts[2-9] based on the combination of a broadband source and a wavelength-dependent receiver. Light-emitting diodes (LED), amplified spontaneous emission (ASE) sources, and ultra-short pulse lasers are typically used as broadband sources. For wavelength-dependent receivers, scanning tunable filters,[3-5] detector-array spectrometers,[3] and unbalanced interferometers[3,7] have been employed. However, these schemes have shown difficulties associated with low signal powers due to the use of a narrow spectral slice from broad source spectrum, poor spectral resolution determined by that of the tunable filter or spectrometer itself, or relatively complex signal processing electronics needed for phase read out.[3] Although it has been recognized that a wavelength-tunable narrowband laser would be a better alternative [Reference?], there has been little effort to date to demonstrate the feasibility of such an approach.

In this Letter we demonstrate an attractive solution for grating sensor array interrogation using a wavelength-swept fiber laser (WSFL).[9] The laser has a scanning tunable filter in the cavity to sweep the laser output wavelength in time continuously and repeatedly over a few tens of nm's range.[10-12] Compared to a current/temperature-tuned diode laser with typically only a few nm's of wavelength tuning,[13] the WSFL described here provides an order of magnitude greater tuning range. When the WSFL output is directed to the grating array, the reflected optical signal consists of a series of pulses in the time domain whose timing, relative to the start of the wavelength sweep, is determined both by the Bragg wavelength of each corresponding grating and its position within the array. By measuring the reflected pulse timing characteristics and employing simple signal processing schemes, based for example on peak detection[4,13] or time interval counting as in this work, one can deduce the instantaneous Bragg wavelength of the individual gratings within the array. This interrogation technique offers several attractive features. Firstly, it provides for high signal powers since the full source output is available for use during the measurement of a given grating's Bragg wavelength. Secondly, the broad source tuning range and narrow instantaneous spectral linewidth allow for a large number of individual elements within the array. Finally, the time domain approach facilitates the discrimination of returns from gratings with spectrally overlapping reflectivity profiles.

Fig. 1 shows the schematic of the experimental setup of (a) the WSFL and (b) the grating array and the signal processing for the time-interval measurements. The

WSFL was in a unidirectional ring configuration with isolators, a 3-dB output coupler, and an Er^{3+}–doped fiber (800 ppm, 6.3-m long) pumped by a laser diode at 1470 nm. A Fabry-Perot (F-P) tunable filter was used as the intra-cavity scanning filter with a 3-dB bandwidth of 0.23 nm and a free-spectral-range of 33 nm. The F-P filter was modulated with a triangular waveform to produce a wavelength sweep over 28 nm from 1538 nm to 1566 nm at a 250-Hz repetition rate. The laser output was directed into both an array of sensing gratings (λ_1 = 1549.3 nm, λ_2 = 1560.4 nm, λ_3 = 1561.9 nm) and a reference grating (λ_0 = 1557.3 nm) via a 50% coupler. The reflectivity and 3-dB bandwidth of the gratings were about 90% and 0.13 nm, respectively. The distance between sensing gratings was approximately 3 m. The signal reflected from the gratings was analyzed with a detector (1-MHz bandwidth) and a conventional time interval counter with a root-mean-square (rms) single-shot resolution of 150 ps. The counter was configured, through use of a suitable arming procedure, to measure the time interval between triggering on the return from the reference grating to triggering on the return from a specified grating within the array.

The threshold launched pump power of the laser was 4 mW. At low pump powers up to about 26 mW, cw output was obtained with random intensity fluctuations of ~10% peak-to-peak (p-p). Interestingly, however, at pump powers above 26 mW and up to a maximum available power of 70 mW, the laser produced mode-locked pulses, one pulse per cavity round trip, at the fundamental repetition rate of 12.14 MHz. The mode-locking mechanism here is attributed to an effective cw-suppression effect by the intra-cavity scanning filter, a detailed discussion of the mode-locking phenomena is beyond the scope of this Letter and will be presented elsewhere. Fig. 2 shows (a) the laser output signal seen using a fast (80 MHz) oscilloscope and detector system illustrating the pulsed nature of the output and (b) the peak-hold optical spectrum . The triangular waveform shown in Fig. 2(a) is the 250-Hz electrical signal applied to the scanning filter. When its voltage was swept upward (downward) the output wavelength increased (decreased). The oscillatory envelope (~5 kHz) of the pulsed laser output is due to the piezo-electric ringing of the F-P filter. By appropriate alignment of the intra-cavity polarization these intensity fluctuations could be reduced to 2-3%. The average output power of the laser was 3.3 mW at a pump power of 60mw (as used in all the experiments described herein), with a variation of less than 1 dB across the full wavelength sweep. Note that although the pulsed output of the current laser configuration was not desirable it did not hinder our demonstration of the principle of this interrogation scheme. The 1-MHz bandwidth of the detector used to measure the reflected optical pulses was sufficient (>>100 kHz) to detect the envelope of the reflected pulses without distortion, but low enough (<<12 MHz) to integrate out the <ns pulse nature of the WSFL output.

Fig. 3(a) shows a typical temporal reflection signal from the gratings measured with the 1 MHz detector. Note that the temporal response has almost the same structure as the actual reflection spectrum of the grating array [Fig. 3(b)] measured with an optical spectrum analyzer (resolution: 0.1 nm) and a broadband ASE fiber source thereby illustrating the excellent linearity of the WSFL wavelength sweep. When the grating λ_2 was strained, its Bragg wavelength and the position of the corresponding reflection pulse shifted as can be seen in the lower traces of Fig. 3. From the width of the pulse (~10 μs) and the measured tuning speed of WSFL (0.016 nm/μs around 1560 nm), the instantaneous linewidth of the laser was estimated to be ~0.09 nm.[12] Fig. 4 shows the measured time differences (a) $\tau_1 - \tau_0$ and (b) $\tau_2 - \tau_0$ in response to static strain applied to gratings λ_1 and λ_2, respectively. The best-fit linear slope coefficients were 73.2 (±0.2) and 74.4 (±0.2) ns/με for (a) and (b), respectively.

The standard deviation of the measured time interval without strain was 35 ns per sampling that corresponding to a strain resolution of 0.47 με rms and limited principally by the laser amplitude noise. Given the sampling period of 4 ms, this represents a system sensitivity of 42 $n\varepsilon/\sqrt{Hz}$. Fig. 5 shows the measured time difference, $\tau_2 - \tau_0$, at 250-Hz sampling rate in the presence of a square-modulated strain applied to the grating λ_2. The p-p amplitude of the varying strain was 4.5 με at 1-Hz frequency.

To further demonstrate dynamic strain measurements we applied 10 Hz and then 100-Hz sinusoidally varying strain to the grating λ_2 with an rms amplitude of 1.6 με (calculated from the displacement of a translation stage used to apply the strain). A set of 512 time interval data points obtained during 2.048 sec was processed with a fast Fourier transform (FFT) analysis. Fig. 6 shows the FFT spectrum averaged over 15 measurement sets for the 100Hz modulation case. The dashed line represents the theoretical noise level due to Gaussian noise with an rms deviation equal to the measured value of 0.47 με. The rms amplitude of the applied strain determined from the height of the spectral peak in Fig. 6 was 0.3 με for the 100 Hz case, and 1.5με for the 10 Hz data as compared to the calculated value of 1.6 με. We believe the discrepancy at higher frequencies to be due to the damping effects of the fiber's soft jacket which was bonded to the translation stage, however this explanation has yet to be confirmed.

The maximum frequency range for dynamic strain measurement without ambiguity was 125 Hz (half the sampling rate). Higher frequency components could also be sensed, since they appear in the same FFT spectrum of 0 to 125 Hz by the aliasing effect, the absolute frequency of the aliased signal could then be measured by dithering the sweep rate.

In conclusion, we have demonstrated a novel application of a wavelength-swept Er^{3+}-doped fiber laser to the interrogation of fiber grating sensor arrays. The WSFL produced an average output power of 3.3 mW, instantaneous linewidth of <0.1 nm, and wavelength scan range over 28 nm. Strain resolution of 0.47 $\mu\varepsilon$ rms with a sampling rate of 250 Hz (42 $n\varepsilon/\sqrt{Hz}$) has been demonstrated.

Acknowledgments

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Fig. 1: Experimental setup for (a) the wavelength-swept fiber laser and (b) the grating sensor array and signal processor.

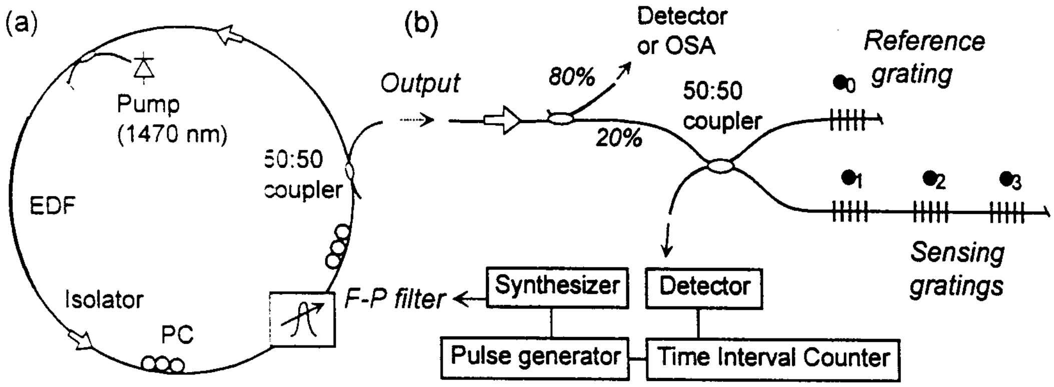

Fig. 2: (a) Triangular modulation signal (upper trace) and WSFL output seen on the oscilloscope. (b) Peak-hold optical spectrum.

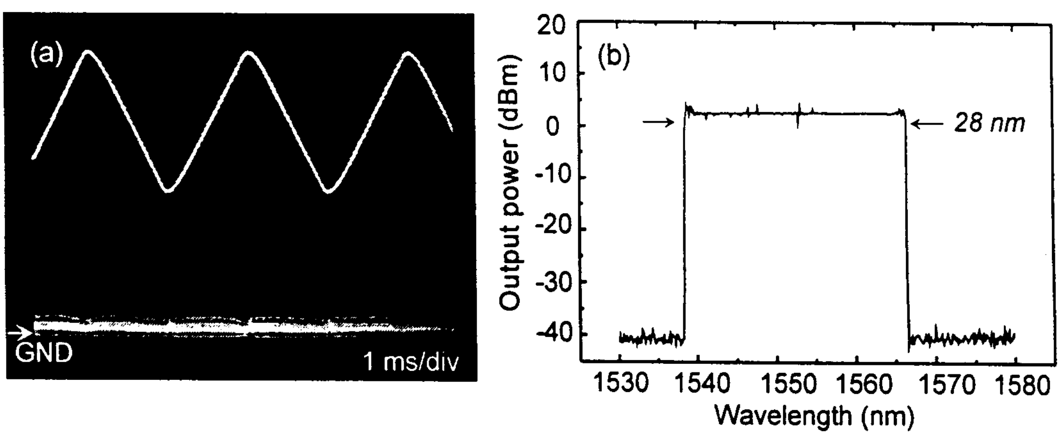

Fig. 3: (a) Time-domain reflection signal of the WSFL output from the gratings. (b) Reflection spectrum of the gratings measured with an ASE erbium fiber source.

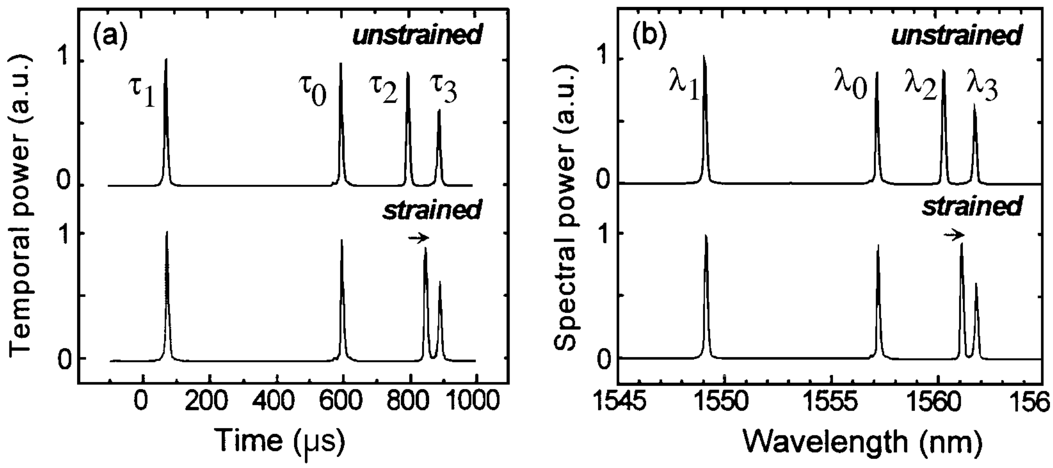

Fig. 4: Measured time difference as a function of strain: (a) τ_1 - τ_0 and (b) τ_2 - τ_0.

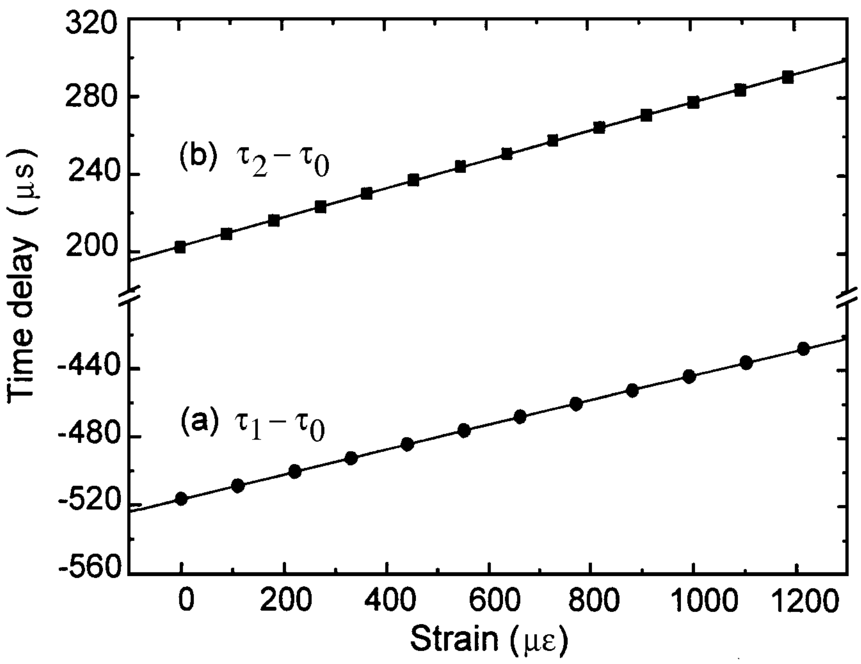

Fig. 5: Measured time difference in response to a square-modulated strain.

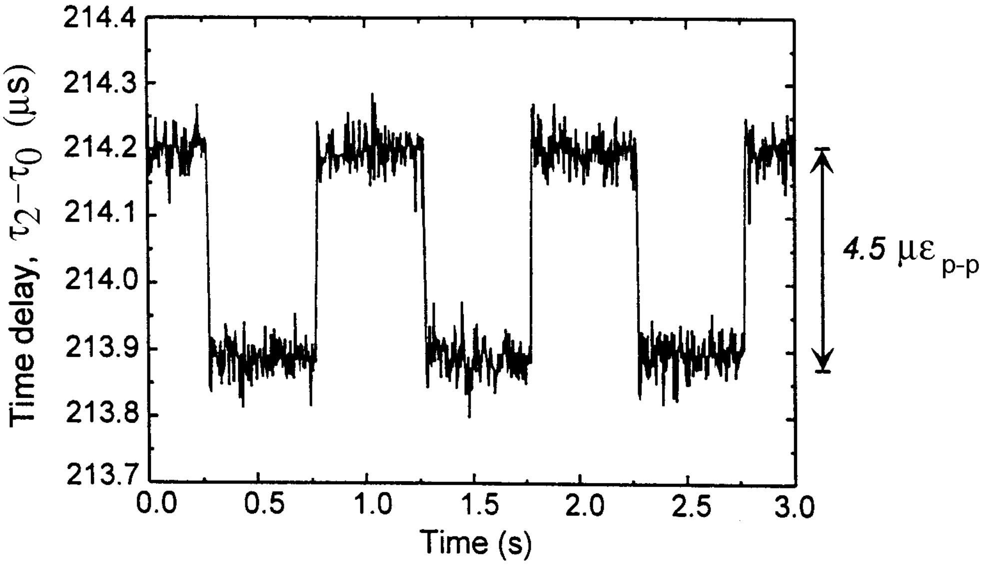

Fig. 6: FFT spectrum of the time interval measurement data for a 100-Hz dynamic strain.