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

Seok Hyun Yun

Department of Physics, Korea Advanced Institute of Science and Technology, 373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea

D. J. Richardson

Optoelectronics Research Center, University of Southampton, Southampton SO17 1BJ, UK

Byoung Yoon Kim

Department of Physics, Korea Advanced Institute of Science and Technology, 373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea

Received January 21, 1998

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 a 28-nm wavelength span. Using time-interval counting, we demonstrate static–dynamic strain measurements with a resolution of 0.47 $\mu\epsilon$ rms at a sampling rate of 250 Hz. © 1998 Optical Society of America

OCIS codes: 060.2370, 060.2380, 140.3460, 140.3500, 140.3510, 140.3600.

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 subsystems of gratings, is determined from induced changes in the individual grating Bragg wavelengths. Various interrogation schemes for the detection of small Bragg wavelength shifts[2–9] based on the combination of a broadband source and a wavelength-dependent receiver have been demonstrated. LED's, amplified spontaneous emission sources, and ultrashort-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 owing to the use of a narrow spectral slice from a broad source spectrum, poor spectral resolution determined by the resolution of the tunable filter or the spectrometer itself, or relatively complex signal-processing electronics needed for phase readout.[3] Although it has been recognized that a wavelength-tunable narrow-band laser would be a better alternative,[6] 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 by use of a wavelength-swept fiber laser (WSFL).[9] The WSFL has a scanning tunable filter in the cavity to sweep the laser output wavelength in time continuously and repeatedly over a range of a few tens of nanometers.[10–12] Compared with a Bragg-grating-tuned fiber laser[6] and a current–temperature-tuned diode laser[13] with typically only a few nanometers of wavelength tuning, 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 by both the Bragg wavelength of each corresponding grating and the position of each grating within the array. By measuring the reflected pulse timing characteristics and employing simple signal-processing schemes based, for example, on peak detection[6,13] or on time-interval counting as in this Letter, one can deduce the instantaneous Bragg wavelength of the individual gratings within the array. This interrogation technique offers several attractive features. First, 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. Second, 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.

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

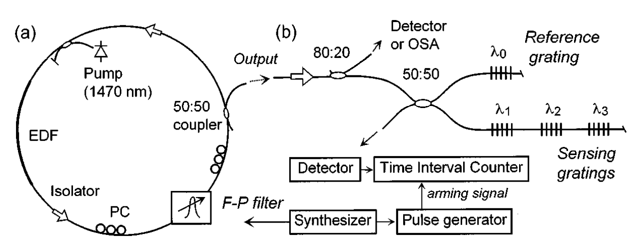

Fig. 1. Experimental setup for (a) the wavelength-swept fiber laser and (b) the grating sensor array and signal processor. EDF, erbium-doped fiber; PC, polarization controller; OSA, optical spectrum analyzer.

0146-9592/98/110843-03$15.00/0

ring configuration with isolators, a 3-dB output coupler, and an Er^{3+}-doped fiber (800 parts in 10^6, 6.3 m long) pumped by a laser diode at 1470 nm. A Fabry–Perot (F–P) tunable filter was used as the intracavity scanning filter and had a 3-dB bandwidth of 0.23 nm and a free spectral range of 33 nm. We modulated the F–P filter with a triangular waveform to produce a wavelength sweep over 28 nm from 1538 to 1566 nm at a 250-Hz repetition rate. The laser output was directed into both an array of sensing gratings ($\lambda_1 =$ 1549.3 nm, $\lambda_2 =$ 1560.4 nm, $\lambda_3 =$ 1561.9 nm) and a reference grating ($\lambda_0 =$ 1557.3 nm) via a 50% coupler. The reflectivity and the 3-dB bandwidth of the gratings were ~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 rms single-shot resolution of 150 ps. We configured the counter by use of a suitable arming procedure to measure the time interval between triggering on the return from the reference grating and 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 ~26 mW, cw output with random intensity fluctuations of ~10% peak to peak was obtained. Interestingly, however, at pump powers greater than 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 produced by the intracavity scanning filter, although a detailed discussion of the mode-locking phenomena is beyond the scope of this Letter. Figure 2(a) shows the laser output signal seen with a fast (50-MHz) oscilloscope and detector system and illustrates the pulsed nature of the output; Fig. 2(b) shows the peak-hold optical spectrum. The triangular waveform shown in Fig. 2(a) is the 250-Hz electrical signal that was applied to the scanning filter. When the signal's voltage was swept upward (downward) the output wavelength increased (decreased). By appropriate alignment of the intracavity polarization controllers the fluctuations of the pulse peak power could be reduced to 3–4%. The average output power of the laser was 3.3 mW at a pump power of 60 mW (as was used in all the experiments described here), 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 ($\gg$100 kHz) to detect the envelope of the reflected pulses without distortion but low enough ($\ll$12 MHz) to integrate out the <1-ns-pulse nature of the WSFL output.

Figure 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 amplified spontaneous emission fiber source, thereby illustrating the excellent linearity of the WSFL wavelength sweep. When 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 the WSFL (0.016 nm/μs near 1560 nm), the instantaneous linewidth of the laser was estimated to be ~0.09 nm.[12] Figure 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 (a) 73.2 $\pm$ 0.2 ns/$\mu\epsilon$ and (b) 74.4 $\pm$ 0.2 ns/$\mu\epsilon$.

The standard deviation of the measured time interval without strain was 35 ns per sampling, which corresponds to a strain resolution of 0.47 $\mu\epsilon$ rms, and was limited principally by the laser amplitude noise.

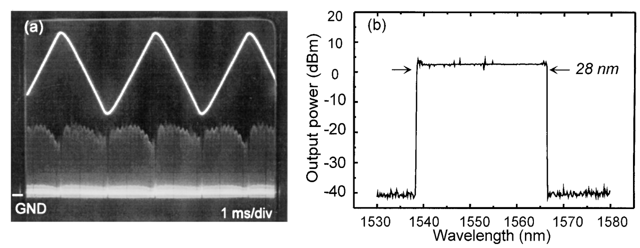

Fig. 2. (a) Triangular modulation signal (upper trace) and WSFL output seen on an oscilloscope. (b) Peak-hold optical spectrum. GND, electrical ground level.

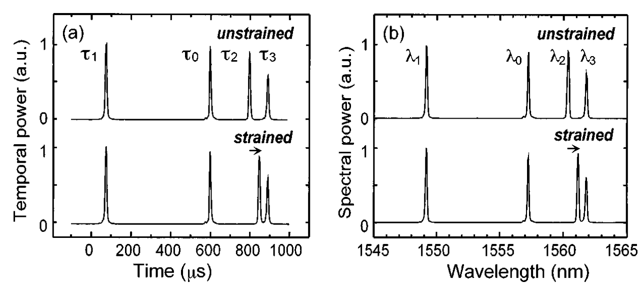

Fig. 3. (a) Time-domain reflection signal of the WSFL output from the gratings. (b) Reflection spectrum of the gratings measured with an amplified spontaneous emission erbium-fiber source.

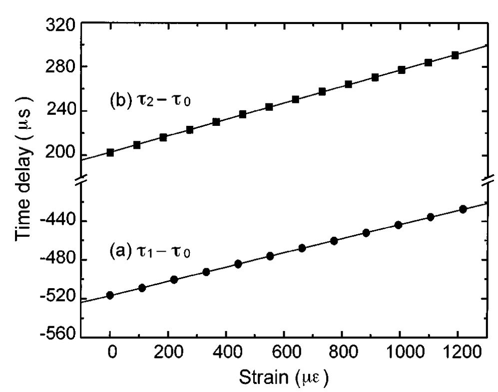

Fig. 4. Measured time difference as a function of strain: (a) $\tau_1 - \tau_0$, (b) $\tau_2 - \tau_0$.

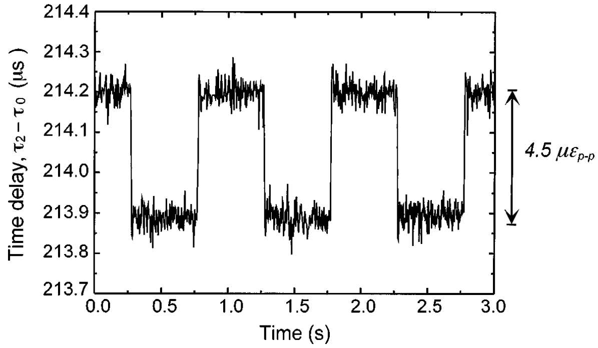

Fig. 5. Measured time difference in the response of grating λ_2 to a square-modulated strain.

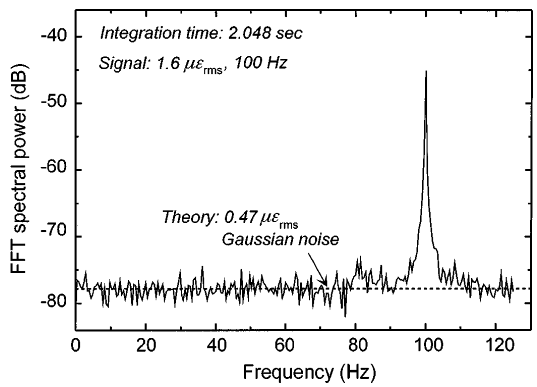

Fig. 6. FFT spectrum of the time-interval measurement data for a 100-Hz dynamic strain.

Given the sampling period of 4 ms, this represents a system sensitivity of 42 $n\epsilon/\sqrt{\text{Hz}}$. Figure 5 shows the measured time difference, $\tau_2 - \tau_0$, at a 250-Hz sampling rate in the presence of a square-modulated strain applied to grating λ_2. The peak–peak amplitude of the varying strain was 4.5 $\mu\epsilon$ at the 1-Hz frequency.

To demonstrate dynamic strain measurements further, we applied 10-Hz and then 100-Hz sinusoidally varying strain to grating λ_2 with a rms amplitude of 1.6 $\mu\epsilon$ (calculated from the displacement of a translation stage that was used to apply the strain). A set of 512 time-interval data points obtained during 2.048 s was processed with a fast Fourier transform (FFT) analysis. Figure 6 shows the FFT spectrum averaged over 15 measurement sets for the 100-Hz modulation case. The dashed line represents the theoretical noise level that is due to Gaussian noise with a rms deviation equal to the measured value of 0.47 $\mu\epsilon$. The rms amplitude of the applied strain determined from the height of the spectral peak in Fig. 6 was 1.3 $\mu\epsilon$ for the 100-Hz case and 1.6 $\mu\epsilon$ for the 10-Hz data; the calculated value was 1.6 $\mu\epsilon$. We believe that the discrepancy at higher frequencies is 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 because of the aliasing effect, and we could then measure the absolute frequency of the aliased signal by dithering the sweep rate.

As the sweep rate and, correspondingly, the wavelength scan speed are increased, changes in the length of the lead fiber sections between gratings owing to environmental conditions can become significant. However, a total length change of as much as 1 m would result in only a 7.8-ns delay in the reflected pulse and would correspond to only 0.11 $\mu\epsilon$ of error for our experimental parameters. This problem was therefore negligible in our experiment.

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, an instantaneous linewidth of <0.1 nm, and a wavelength scan range over 28 nm. A strain resolution of 0.47 $\mu\epsilon$ rms with a sampling rate of 250 Hz (42 $n\epsilon/\sqrt{\text{Hz}}$) was demonstrated.

S. H. Yun acknowledges the financial support of the Korea Research Foundation in program year 1997. D. J. Richardson was supported by the Royal Society under the provision of a Royal University Fellowship.

References

1. W. W. Morey, G. Meltz, and W. H. Glenn, Proc. SPIE **1169,** 98 (1989).
2. S. M. Melle, K. Liu, and R. M. Measures, IEEE Photon. Technol. Lett. **4,** 516 (1992).
3. A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. D. Askins, M. A. Putnam, and E. J. Friebele, J. Lightwave Technol. **15,** 1442 (1997).
4. A. D. Kersey, T. A. Berkoff, and W. W. Morey, Opt. Lett. **18,** 1370 (1993).
5. M. G. Xu, H. Geiger, J.-L. Archambault, L. Reekie, and J. P. Dakin, Electron. Lett. **29,** 1510 (1993).
6. G. A. Ball, W. W. Morey, and P. K. Cheo, J. Lightwave Technol. **12,** 700 (1994).
7. Y. J. Rao, D. A. Jackson, L. Zhang, and I. Bennion, Opt. Lett. **21,** 683 (1996).
8. M. L. Dennis, M. A. Putnam, J. U. Kang, T.-E. Tsai, I. N. Duling III, and E. J. Friebele, Opt. Lett. **22,** 1362 (1997).
9. S. H. Yun and B. Y. Kim, in *Optical Fiber Sensors,* Vol. 16 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), postdeadline paper PD2; a preliminary part of the present study was presented at this meeting.
10. P. F. Wysocki, M. J. Digonnet, and B. Y. Kim, Opt. Lett. **15,** 879 (1990).
11. P. Zorabedian, J. Lightwave Technol. **13,** 62 (1995).
12. S. H. Yun, D. J. Richardson, D. O. Culverhouse, and B. Y. Kim, IEEE J. Select. Topics Quantum Electron. **3,** 1087 (1997).
13. T. Corey, L. M. Chappell, N. J. Guillermo, S. Y. Huang, and R. M. Measures, in *Optical Fiber Sensors,* Vol. 16 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), paper OWC17.