Highly sensitive dynamic strain measurements by locking lasers to fiber Bragg gratings

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A novel, sensitive, simple, and robust strain interrogation technique is analyzed and experimentally tested. By locking a laser wavelength to the midreflection wavelength of a standard fiber Bragg grating and measuring the error signal, we achieve high dynamic strain sensitivity of 45 picostrain/$\sqrt{\mathrm{Hz}}$ rms at 3 kHz, where the dominant noise in the experiment is the laser frequency noise.

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Owing to their fiber-based, wavelength-encoded operation, fiber Bragg gratings (FBG's) offer attractive sensing possibilities, especially in strain, and temperature embedded sensors for smart structures.[1] Typical sensitivities of FBG strain sensors are near 1 microstrain/$\sqrt{\mathrm{Hz}}$ rms.[1] Much higher sensitivities require an interferometric wavelength-shift detection scheme[2,3] or special π-shifted FBG's.[4] In this Letter we present a novel, passive, and narrow-band interrogation method for FBG strain measurements that is capable of very high sensitivity and high resolution, in a simple and robust scheme that provides direct electronic demodulation.

The principle of operation is the following: The wavelength of a single-longitudinal-mode laser is tuned to the midreflection wavelength of a FBG, and the reflected light is measured by a photodetector (PD1); see Fig. 1. A low-gain, narrow-band servo continuously controls the laser wavelength to keep it locked to the midreflection wavelength of the FBG, thereby stabilizing the operating point against slow temperature and strain drifts as well as frequency drifts of the interrogating laser. However, the laser wavelength will not track dynamic strain variations at frequencies above the unity gain frequency of the servo. The dynamic strain will shift the reflection curve of the FBG, and hence the reflected power from the grating will vary in proportion to the applied strain. The dynamic strain can thus be derived directly from the ac photocurrent of the reflected signal.

Assuming a linearized reflection curve of the FBG, we can model the reflection coefficient R_f of the free, unstrained FBG around the midreflection point as (see the inset of Fig. 1)

$$R_f(\nu) = R_0 + (\nu - \nu_0)G\,, \tag{1}$$

where ν is the optical frequency, G is the grating reflectivity slope, and ν_0 and R_0 [$=R_f(\nu_0)$] are the midreflection frequency and the reflection coefficient of the free fiber, respectively. An applied strain ε will shift the FBG reflection curve by $\Delta\nu_s$, which we experimentally confirmed to obey $\Delta\nu_s/\nu = -0.79\varepsilon$.[1] The reflection curve of the strained fiber therefore becomes $R_f(\nu - \Delta\nu_s)$. When an input light with a power level of P_0 is sent toward the grating, the reflected signal generates at PD1 a photocurrent $I_r(\nu) = R_f(\nu - \Delta\nu_s)R_D P_0$, where R_D is the detector responsivity. If we close the control loop at the midreflection point, R_0, the servo will vary the laser frequency so that the dc photocurrent is maintained at $R_0 R_D P_0$ even in the presence of a slowly varying strain (or temperature). A dynamic strain at a frequency exceeding the unity gain frequency of the servo will generate an ac photocurrent of the form

$$\begin{aligned} i_r &= [R_f(\nu - \Delta\nu_s) - R_0]R_D P_0 \\ &= -G\Delta\nu_s = (0.79\nu G R_D P_0)\varepsilon\,, \end{aligned} \tag{2}$$

from which the strain is easily determined.

Unlike other interrogation architectures that use broadband sources,[2] our narrow-band technique provides the detector with enough optical power ($\sim$100 μW) that all detector noise contributions are negligible. The fundamental sensitivity limits of this sensing technique are set by the shot noise and the spontaneous-emission-induced frequency noise of the laser. The average photocurrent $R_0 R_D P_0$ is accompanied by shot noise, which will be interpreted as strain

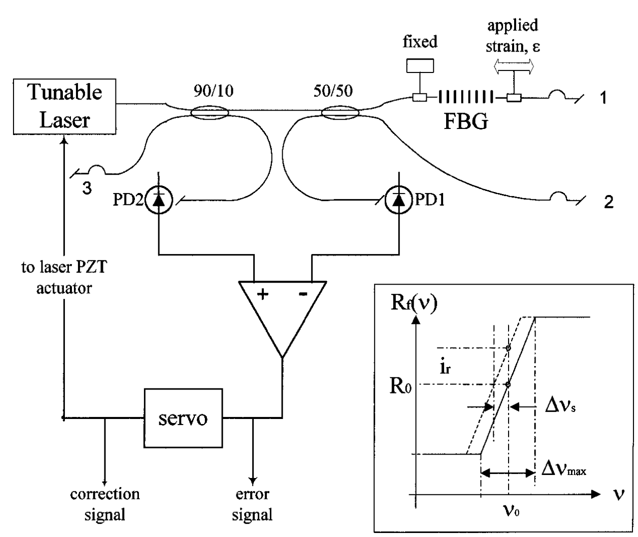

Fig. 1. Dynamic strain measurement setup. Inset, effect of applied strain on the FBG reflectivity curve. See text for definitions.

noise. Using Eq. (2) and assuming typical values of $R_0 = 0.5$, $R_D = 1$ A/W, $P_0 = 100\ \mu$W, $G = 35\ \text{GHz}^{-1}$, and $\nu = 195$ THz (1540 nm), we find that the minimum detectable strain is $\varepsilon_{\min(\text{shot})} = 9 \times 10^{-12}/\sqrt{\text{Hz}}$. The laser intensity noise should also be considered. For a fairly low-noise laser with a relative intensity noise of -145 dB/Hz the minimum detectable strain becomes $\varepsilon_{\min(\text{RIN})} = 6 \times 10^{-12}/\sqrt{\text{Hz}}$.

The second fundamental limitation is the spontaneous-emission-induced frequency noise of the laser. In an ideal laser only the spontaneous-emission process contributes to the laser frequency noise. In this case the laser linewidth is Lorentzian with a linewidth $\Delta\nu_L$, and the frequency-noise power spectral density is $S_f = \Delta\nu_L/\pi$ in units of hertz squared per hertz.[5] This frequency noise, which is interpreted by the FBG as strain noise, will set a limit on the sensor sensitivity of

$$\varepsilon_{\min(\text{freq})} = \sqrt{S_f}/0.79\nu \qquad (3)$$

for a 1-Hz bandwidth. For a typical tunable external-cavity semiconductor laser $\Delta\nu_L = 1$ MHz, $\sqrt{S_f} = 560\text{Hz}/\sqrt{\text{Hz}}$, and $\varepsilon_{\min(\text{freq})} = 3.6 \times 10^{-12}/\sqrt{\text{Hz}}$. In practice, the frequency-noise spectral density is often higher than the level induced by spontaneous emission, owing to technical noises caused, for example, by acoustic and thermal disturbances. Depending on the frequency-noise level, the sensitivity can be limited either by the frequency noise or by the shot noise. Another noise contribution is thermally induced refractive-index fluctuations,[6] which will induce frequency fluctuations of the FBG reflection curve. However, one obtains for a 1-cm-long FBG a strain sensitivity limit of $\varepsilon_{\min(\text{thermal})} < 10^{-13}/\sqrt{\text{Hz}}$, which is negligible with respect to the shot noise and the laser frequency noise.

The linear dynamic range of the measurable strain is determined by the spectral width $\Delta\nu_{\max}$ of the linear section in the FBG reflectivity curve (inset of Fig. 1). Thus the highest peak-to-peak measurable dynamic strain becomes $\varepsilon_{\max} = \Delta\nu_{\max}/0.79\nu$. To achieve a larger $\varepsilon_{\max}$ one should increase $\Delta\nu_{\max}$, which is equivalent to reducing the reflectivity-versus-wavelength slope; this will also increase the shot- and intensity-noise contributions but will have no effect on the frequency-noise contribution. Hence, if the system is limited by frequency noise, it is worthwhile to increase $\Delta\nu$ to a critical value at which the shot-noise contribution becomes equal to the frequency-noise contribution. Increasing $\Delta\nu$ will increase dynamic range without reducing sensitivity. Comparing the sensitivity limits imposed by the frequency noise [Eq. (3)] with those imposed by the shot noise and assuming a FBG slope of $G = 2R_0/\Delta\nu_{\max}$, we find that the critical $\Delta\nu_{\max}$ is given by

$$\Delta\nu_{\max,\,\text{critical}} = (2R_0 R_D P_0 S_f/e)^{1/2}. \qquad (4)$$

Using the values given above, we find that $\Delta\nu_{\max,\,\text{critical}} = 14$ GHz and $\varepsilon_{\max} = 90$ microstrain peak to peak. With a proper design of the FBG, e.g., by use of a very short FBG or a chirped and strongly apodized grating with an asymmetric reflectivity profile,[7,8] the dynamic range can be increased as desired but at the expense of sensitivity and resolution. FBG's with a moderate and asymmetric reflection slope and a bandwidth exceeding 15 nm are now commercially available,[9] enabling one to achieve a larger dynamic range limited by the tensile strength of the fiber.

We constructed this FBG strain sensor and experimentally tested its performance, using the setup shown in Fig. 1. The light source is a tunable diode laser (New Focus Model 6262). The laser frequency can be continuously tuned over 35 GHz by an internal piezoelectric (PZT) frequency actuator. Coarse wavelength tuning over a wider tuning range (1491–1568 nm) is achieved by use of another PZT actuator. The laser light is coupled into the fiber after it passes through an optical isolator. The FBG reflection, centered at 1540 nm with a peak reflection of ≥96%, has a FWHM of 1.5 nm and a linear slope width $\Delta\nu = 35$ GHz. We glue the fiber to a PZT-actuated mount to generate dynamic strain calibration signals. To eliminate parasitic interference between the FBG and all fiber terminations we use angled connectors and tightly bend all the unused fiber ports. The typical power level at each detector is 100 μW. An error signal for locking to the midreflection point is obtained by subtraction of the reflected signal (at PD1) from a reference signal (at PD2). The servo includes an integrator and a variable amplifier. The typical open-loop gain of our system as a function of the electrical frequency f is $\approx 20/f$, and hence the system is suitable for measuring dynamic strain signals at $f > 20$ Hz. The laser remains locked to the FBG for several hours without any further adjustments. Without this servo, the laser frequency will slowly drift away from the operating point at the midreflection wavelength of the FBG. The inset of Fig. 2 shows an oscilloscope trace of the error signal when the PZT-actuated fiber holder applied a sinusoidal strain signal at 1 kHz.

To measure the sensitivity, we applied a 27-nanostrain (rms) calibration signal by modulating the PZT actuator at 3 kHz. The power spectral density

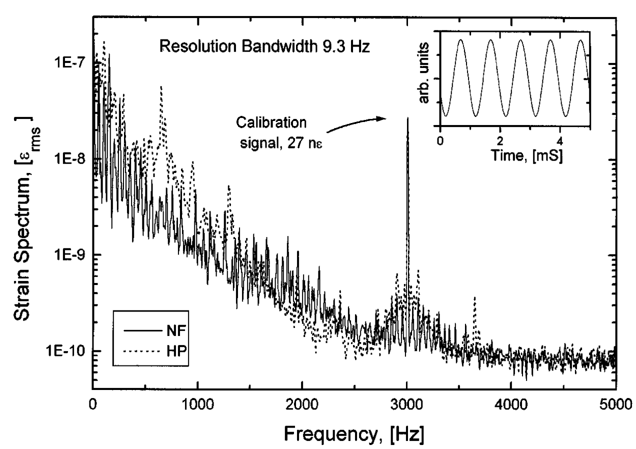

Fig. 2. Measured strain resolution spectrum obtained with New Focus (NF) and Hewlett-Packard (HP) laser sources. Inset, error signal for a 1.5-microstrain (rms) strain signal at 1 kHz.

of the error signal is measured with a fast Fourier transform spectrum analyzer (see Fig. 2). Since the observed signal/noise ratio is 46 dB and the resolution bandwidth is 9.3 Hz, the sensitivity at 3 kHz is $\approx$45 picostrain/$\sqrt{\text{Hz}}$ rms (130 picostrain/$\sqrt{\text{Hz}}$ peak to peak). Assuming linear behavior of the sensor, this result is also the sensor resolution. We tested the system with another external-cavity diode laser source (Hewlett-Packard Model 8168C). The wavelength of this laser cannot be continuously tuned, and hence we could not lock it to the FBG. However, since the relative drift between the laser and the FBG is fairly slow, we simply tuned the laser to the midreflection wavelength and immediately measured the intensity-noise spectrum of the reflected signal (see Fig. 2). The sensitivity in this case is similar to that obtained with the New Focus laser. The intensity noise of the signal transmitted through the FBG was considerably higher at the midreflection wavelength than outside the FBG reflection band, which clearly indicates that the system is not limited by shot noise or laser intensity noise. Since the two tested lasers showed slightly different noise spectra, we have to rule out the possibility that the background noise is extrinsic to the system (e.g., ambient acoustical noise). Hence, it appears that the dominant noise above 300 Hz is laser frequency noise. Assuming laser frequency noise–limited measurement, the measured sensitivity is equivalent to laser frequency noise with a power spectral density of $\sqrt{S_f} = 7\ \text{kHz}/\sqrt{\text{Hz}}$ at 3 kHz.[10] The sensitivity deteriorates at lower frequencies, with a sensitivity of $\approx$1 nanostrain/$\sqrt{\text{Hz}}$ at 500 Hz, comparable with the best reported strain-sensing results for a single FBG, obtained with an unbalanced interferometric wavelength discriminator.[2] Extremely high sensitivities, $\approx$7 femtostrain/$\sqrt{\text{Hz}}$ at 7 kHz, were measured with a Bragg grating laser and a 96-m shielded readout interferometer.[3] In this case, however, the sensing length was the entire 3 m of the laser cavity, whereas with a single FBG sensor, as was used in Ref. 2 and in our work, the sensor is well localized at the position of the FBG. High strain sensitivity was recently obtained with a special π-shifted FBG sensor.[4] However, as demonstrated in this Letter, comparable or even slightly better sensitivity can be achieved with a standard FBG.

Since the width of the linear range of the FBG is $\Delta\nu_{\max} = 35$ GHz, the largest measurable peak-to-peak strain is 227 microstrain, and the dynamic range is therefore 125 dB in a 1-Hz bandwidth. As mentioned above, the largest measurable strain and the dynamic range can be further increased by use of a different FBG with a wider range of reflection slope. The high sensitivity and resolution can be maintained, since the dominant noise is apparently the laser frequency noise.

Another operating mode is to make the unity gain frequency of the servo higher than the strain signal frequencies of interest. In this high-gain mode, the strain information appears on the correction signal, which could potentially lead to a larger dynamic range, limited by the maximum continuous tuning range of the laser and not by the FBG characteristics.

In summary, we have demonstrated a novel, simple, narrow-band interrogation method of FBG and obtained high strain sensitivity of 45 picostrain/$\sqrt{\text{Hz}}$ rms at 3 kHz with a dynamic range of 110 dB (measured). The sensitivity and resolution appear to be limited by the frequency noise of our source. Further improvement can be achieved by use of a source with lower frequency noise, such as diode-pumped solid-state lasers, which exhibit a frequency-noise spectral density of $\sqrt{S_f} = 50\ \text{Hz}/\sqrt{\text{Hz}}$.[10] One can time multiplex several FBG sensing elements by sequentially locking them to each FBG, measuring the strain, and tuning the laser wavelength to the next FBG.

The current experimental setup cannot measure static strain yet, since very slow (static) variations of the locking point can be attributed either to strain variations of the FBG or to drift of the laser frequency. However, we can reduce the laser frequency drift to the submegahertz level by locking the laser frequency to atomic[11] or molecular absorption lines. This reduction should enable us to perform highly sensitive static strain measurements as well.

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References

1. A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. J. Askins, M. A. Putnam, and E. J. Friebele, J. Lightwave Technol. **15,** 1442 (1997).
2. A. D. Kersey, T. A. Berkoff, and W. W. Morey, Electron. Lett. **28,** 236 (1992).
3. K. P. Koo and A. D. Kersey, J. Lightwave Technol. **13,** 1243 (1995).
4. M. LeBlanc, A. D. Kersey, and T. Tsai, in *Optical Fiber Sensors*, Vol. 16 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), pp. 28–30.
5. D. S. Elliot, R. Roy, and S. J. Smith, Phys. Rev. A **26,** 12 (1982).
6. S. Knudsen, A. B. Tveten, and A. Dandridge, IEEE Photon. Technol. Lett. **7,** 90 (1995).
7. A. D. Kersey, M. A. Davis, and T. Tsai, in *Proceedings of the 11th International Conference on Optical Fiber Sensors (OFS-11)* (IEEE-LEOS, Piscataway, N.J., 1996), pp. 634–637.
8. K. Sudgen, I. Bennion, A. Molony, and N. Copner, Electron. Lett. **30,** 440 (1994).
9. For example, Innovative Fibers, 45 De Villebois, Suite 200, Gatineau, Quebec J8T 8J7, Canada.
10. K. J. Williams, A. Dandridge, A. D. Kersey, J. F. Weller, A. Yurek, and A. B. Tveten, Electron. Lett. **25,** 774 (1989).
11. V. Mahal, A. Arie, M. A. Arbore, and M. M. Fejer, Opt. Lett. **21,** 1217 (1996); A. Bruner, A. Arie, M. A. Arbore, and M. M. Fejer, Appl. Opt. **37,** 1049 (1998).