Supporting Online Material for

Probing the Ultimate Limit of Fiber-Optic Strain Sensing

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This PDF file includes:

Materials and Methods
Figs. S1 and S2
References
Materials and Methods

1. Fiber cavity lock

The fiber Bragg-grating resonator sensor is interrogated by an extended-cavity diode laser emitting around 1560 nm (Toptica DL100). A portion of the laser beam is phase modulated by a fiber electro-optic modulator (EOM), generating sidebands at 28 MHz, before being directed to the sensor. Ideal impedance matching of the optical field to the cavity is achieved when the laser is slightly detuned from the peak FBG reflectivity region, namely for a Finesse $F \approx 110$. The cavity reflected light is collected by a fiber circulator for frequency locking of the laser (SC) with a Pound-Drever-Hall (PDH) scheme (S1). Two ‘secondary carriers’ (SCs) are created by additional phase modulation from a synthesizer equipped with an external analogue frequency-modulation input (maximum range ± 40 MHz). Its 40-MHz output is first multiplied by 8 (320 MHz) to extend the frequency-modulation range up to 640 MHz, and then added to the EOM electrical input (Fig. 1). Beat signals at 28 MHz from the detector are demodulated in a double-balanced mixer that yields the typical PDH discriminator across the resonance for the two SCs. This signal is sent to a proportional-integrator servo that drives the synthesizer to lock one of the SCs to a cavity mode within a bandwidth of 40 kHz. The servo output provides the strain readout. The maximum measurable strain is presently limited to about 4 $\mu e_{\text{rms}}$ due to the frequency-modulation range allowed by our synthesizer (0-640 MHz).

2. Laser phase lock to the optical comb

The optical frequency comb (OFC) consists of a mode-locked erbium-fiber laser (Menlo Systems FC1500) whose repetition rate $f_r$ and carrier-envelope offset frequency $f_o$ are phase locked to the $25^{th}$ and $2^{nd}$ harmonics of a 10-MHz oven-controlled quartz oscillator (OCXO), respectively. The free-running oscillator exhibits a single-sided phase
noise $L(f) \approx -122$ dBC/Hz at 1 Hz and an Allan variance of $10^{13}$ for 1 s. For time scales longer than 400 s, the OCXO is phase linked to a local Rb-clock, which is ultimately disciplined by the primary Cs-standard via a GPS receiver for compensation of very-long term instabilities. The RF beat note between the laser and the comb nearby 192 THz is sent to a digital-analogue phase and frequency detector (PFD) to phase lock the laser to the nearest comb tooth with a frequency offset given by a 30-MHz local oscillator (S2). The beat and lock unit consists of a beat-note detection interferometer and a digital-analogue phase and frequency detector (PFD) to realize a phase-locked loop (PLL) (S3). The PLL rules a 3-paths servo acting simultaneously on the extended-cavity piezo, the diode current supply and a bias-tee input with an overall bandwidth of 1.5 MHz (Fig. S2). The feedback controls the laser frequency to maintain the laser-comb offset equal to 30 MHz (namely, the OCXO frequency $\times 3$).

3. Conversion of laser frequency changes to strain

The laser frequency $\nu$ can be related to the comb repetition rate $f_r$ and the carrier-envelope offset frequency $f_o$ through the expression

$$\nu = \pm f_{\text{beat}} \pm f_o + m \cdot f_r, \quad (1)$$

where $f_{\text{beat}}$ is the laser-comb beat-note frequency and $m$, a large integer, is the tooth number. In our interrogation scheme, the SC synthesizer frequency adds to the term $f_{\text{beat}}$. All quantities in Eq. 1 can be measured using a frequency counter (S2).

Treating the OFC as a ‘rigid’ multiplication gear of the OCXO with a scale factor $N (N \sim 192 \text{ THz}/10 \text{ MHz} = 1.9 \times 10^7)$, the laser can in principle approach a frequency noise spectral density of $S_r(f) = N \cdot f \cdot \sqrt{2L(f)} \approx 20 \text{ Hz}/\sqrt{\text{Hz}}$ at 1 Hz. Any optical frequency fluctuation $\delta \nu$ is converted into strain $\varepsilon$ according to the relation

$$\varepsilon = \frac{1}{k} \frac{\delta \nu}{\nu} \quad (2)$$

where $k = 0.74$ is the normalized fiber responsivity to strain at 1550 nm (4). Given the laser frequency noise, Eq. (2) yields a strain noise level $\approx 140 \text{ f}e/\sqrt{\text{Hz}}$ (the minimum is 120 $\text{f}e/\sqrt{\text{Hz}}$ at 2 Hz).
Fig. S1. To better understand the origin of the ultimate sensitivity limit (Fig. 3), we compare the strain noise spectral density observed with the OCXO and that observed using a reference oscillator with a worse phase stability. A noise level of about -80 dBC/Hz (black line) does not lead to the expected 40-dB degradation with respect to the OCXO level at 2 Hz (red line).

Fig. S2. The main trace represents the closed loop beat note signal between the laser and OFC on a wide frequency span (resolution bandwidth 10 kHz). The servo bumps at 1.5 MHz are due to the fast part of the PLL. The expanded spectrum in the inset shows a sharp spectral feature with a width equal to the analyzer bandwidth (20 mHz).
References