Quasi-static Fiber Strain Sensing with FM Spectroscopy

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Abstract: We present a highly sensitive detection system for quasi-static strain, employing FM spectroscopy with a gas cell as absolute frequency reference, demonstrating a few tens of pε/√Hz sensitivity between 1 - 6 Hz.

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1. Introduction

Interferometric fiber sensing often utilize changes in optical path length (OPL) in fiber to produce a readout. Since the OPL of the fiber can be affected by pressure, temperature, effective index change, acoustic and mechanical strain amongst other effects, this change in OPL can be used to provide a measurement for the quantity of interest. Any OPL change in a length of fiber can also be expressed as effective strain if the fiber length under test is known. A high resolution fiber strain measurement, therefore, is a powerful tool for numerous sensing applications. For measurement of physical quantities such as pressure, temperature, gaseous and liquid trace concentrations, and mechanical strain in smart structures, the resultant change in OPL is typically slow. Hence they are usually considered quasi-static strain sensing, where the signal frequencies are below 10 Hz. High resolution quasi-static strain sensing is usually dominated by seismic, mechanical noise and thermal drifts, affecting both the laser source as well as the sensing device. To mitigate the effect of environmental noise, experiments reporting some of the highest quasi-static strain sensitivities in the literature use frequency references for the laser. Spectroscopic frequency references are extremely useful in quasi-static strain sensing due to their stability and immunity from mechanical and thermal perturbations.

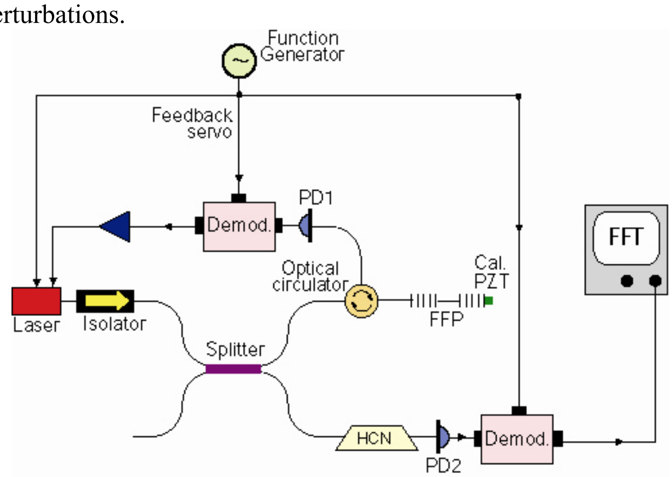

Fig. 1. The experimental schematic for the absolute frequency referenced strain sensing system. It shows the control loop for locking the laser to a FFP, while the HCN gas cell is used to extract the strain signals as experienced by the FFP.

In this paper we demonstrate a technique for measuring quasi-static strain with pico-strain resolution. The technique uses a molecular absorption transition of a hydrogen cyanide (HCN) gas cell as an absolute frequency reference, to readout the strain signal as detected by a fiber Fabry-Perot (FFP) interferometer. To faciliate this, we employ radio-frequency (RF) modulation interferometry, similar to the Pound-Drever-Hall [1] and frequency modulation spectroscopy techniques [2], for both frequency locking and strain signal extraction.

2. Experimental Technique

The schematic of our experimental setup is illustrated by Fig. 1. The laser source is a commercial DFB diode laser at ~1550.5 nm, with about 0.2 nm of tuning range via its drive current. The function generator provides the 80 MHz RF voltage for modulating the current of the diode laser, and the local oscillator for demodulating the reflected light from the FFP strain detector, and transmitted light from the HCN gas cell.

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After the optical isolator, the laser is split into two paths by the 2x2 fusion tapered coupler. The first is used to interrogate the FFP. The reflected light from the FFP is directed by the optical circulator to photodetector PD1. Its RF electronic output is then demodulated to provide the error signal. The frequency servo uses this error signal to feedback to the diode laser, which locks the laser to the FFP resonance. The FFP is a resonator comprising of two Bragg gratings with nominal peak reflectivities of 95%, separated by 80 mm. It is housed in an anechoic chamber to isolate it from laboratory environmental noise. The FFP also has a piezo-electric transducer (PZT) attached to provide a calibration strain signal. The second laser beam is transmitted through a HCN gas cell at 10 Torr, where it is received by photodetector PD2. The FFP is stretch tuned so that its resonance coincides with that of a HCN absorption transition. The FFP resonance has a FWHM of ~50 MHz, while the absorption transition of the HCN cell is approximately 1 GHz wide. The HCN absorption line is the P11 transition of the $2\nu_3$ band.

When the laser is locked, any changes in the measurand causes an OPL change in the FFP. This results in a relative frequency detuning between the FFP resonance (and hence the laser) and the HCN transition. When the system is operated within the linear portion of the HCN error signal, the output voltage is proportional to the frequency detuning, and thus the strain in the FFP. The HCN error signal, therefore, can be used to extract strain information as experienced by the FFP. This is done by performing a Fast Fourier Transform (FFT) on the HCN error signal with a dynamic signal analyzer.

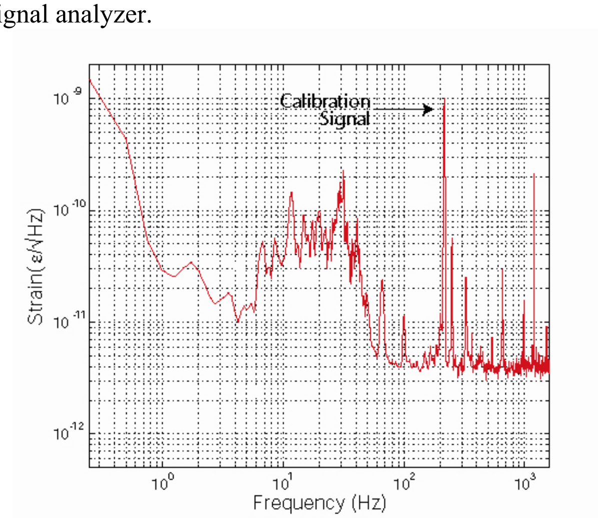

Fig. 2. The FFT of the HCN error signal while the laser is locked to the FFP, as observed with a dynamic signal analyzer. The strong peak at 216 Hz is the calibration strain signal introduced by the PZT attached to the FFP.

3. Results and Discussion

The performance of our system is displayed in Fig. 2. We used the PZT attached to the FFP to introduce a calibration strain of 1×10^{-9} ε/√Hz, as evidenced by the strong peak at 216 Hz. This is then used to scale the vertical axis to provide the strain sensitivity. It can be seen from the plot that above strain frequencies of 100 Hz, the sensitivity noise floor is at about 4 pε /√Hz. This was likely limited by the frequency noise of the diode laser.

There is a cluster of noise from about 6 Hz to 50 Hz, where the sensitivity degraded to just below 100 pε/√Hz. This is due to residual laboratory noise which the anechoic housing for the FFP was unable to mitigate, and includes mechanical resonances of the housing, mounting and optical table, excited by environmental perturbations. Below 6 Hz, the sensitivity is around 10 pε/√Hz, worsening to about 30 pε/√Hz at 1 Hz. The quasi-static strain sensitivity of our experiment below 6 Hz is dominated by electronic noise in the mixer. To the best of our knowledge, this sensitivity is at least an order of magnitude improvement over the highest result demonstrated in literature [3].

4. References

[1] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, "Laser phase and frequency stabilization using an optical resonator," Appl. Phys. B,**31**, 97--105 (1983).

[2] X. Zhu and D. Cassidy, "Modulation spectroscopy with a semiconductor diode laser by injection-current modulation," JOSA B, **14**, 1945--1950 (1997).

[3] Ady Arie, Boaz Lissak, and Moshe Tur, "Static fiber-Bragg grating strain sensing using frequency-locked lasers," J. Lightwave Technol., **17**, 1849--1855 (1999).