Sub-mK and nano-strain discrimination using frequency stabilized lasers and polarization maintaining π-shifted fibre Bragg gratings

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Abstract: We report on a sensing system which discriminates strain and temperature with 5.5 nano-strain and 0.39 mK resolutions respectively. The system deploys frequency stabilized integrated InP-based lasers and a heterodyne-based read-out system. ©2020

1. Introduction

Fibre Bragg gratings (FBG) are attractive as transducers for fibre-based sensing due to their small size and weight, versatility, modularity and immunity to electromagnetic radiation [1]. The measurement of strain is important in structural health monitoring of man-made structures such as bridges and buildings, wings of planes and monitoring of seismic activity in geophysical research. FBG-based strain sensors can potentially offer the desired resolution in the aforementioned applications [1-3]. However, temperature variations limit the accuracy of strain sensors and hinder their deployment for nε measurement and below. The degradation of strain sensing accuracy due to temperature variations is often called cross-sensitivity. The cross-sensitivity problem is especially pronounced in the nε regime where even mK variations in temperature become significant. Considering the typical strain and temperature sensitivities standard single-mode fibre (SSMF), e.g. 120 kHz/nε (nano-strain, nm/m) and 1.2 MHz/mK [1], a couple of mK temperature variation would entirely obscure strain measurements at the nε level.

Various solutions to the cross-sensitivity problem have been proposed; such as the direct compensation of temperature variations using a strain-isolated fibre, use of a single grating as a first and second order grating at the same time and the use of gratings written on spliced fibres with different cross-sections i.e. SSMF and micro-structured fibres. All these approaches are based on the measurement of two optical parameters, e.g. the shift of two resonances. Another method is the use of FBGs written on a polarisation-maintaining (PM) fibre which results in two distinct resonances for the fast- and slow-axis, depending on the polarization of light. The birefringence of the fibre is dependent on both strain and temperature. The best results have been demonstrated using the latter approach, in a system which deploys side-band frequency locking of a commercial narrow linewidth laser to a PM π-shifted FBG [3]. The demonstrated resolutions where 18 nε and 1.4 mK with 2 Hz read-out speed.

In this work, we demonstrate a system which can discriminate strain and temperature effects with 5.5 nε and 0.39 mK resolutions at 2.5 Hz read-out speed. The system is based on frequency stabilized InP lasers fabricated using foundry technology, a PM π-shifted FBG and heterodyne-based read-out system with a frequency counter.

2. Principles of strain and temperature discrimination with polarization maintaining π-shifted FBG

The π-shifted FBGs differ from uniform FBGs in that these offer a narrower spectral feature (~100 MHz full-width at half-maximum), the central frequency of which can be more accurately defined. The transmission spectrum of such a structure written on a PM fibre exhibits two narrow notches, one for the fast- and one for the slow-axis (Fig. 1(a)) with frequencies $\boldsymbol{v_f}$ and $\boldsymbol{v_s}$ respectively, due to the fibre birefringence. The frequency shift of these two resonances, $\Delta\boldsymbol{v_f}$ and $\Delta\boldsymbol{v_s}$, due to strain and temperature differ by a small amount as indicated in Fig. 1(b), typically <5% for temperature and <1% for strain. The frequency shifts depend on the strain and temperature sensitivities $\boldsymbol{S_s^\varepsilon}$, $\boldsymbol{S_f^\varepsilon}$, $\boldsymbol{S_s^T}$ and $\boldsymbol{S_f^T}$ of the two axes. By measuring the frequency shifts and solving the following linear system of equations [4]

$$\begin{bmatrix} \Delta v_s \\ \Delta v_f \end{bmatrix} = \begin{bmatrix} S_s^T & S_s^\varepsilon \\ S_f^T & S_f^\varepsilon \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} \quad (1)$$

one can retrieve the applied strain $\Delta\varepsilon$ and temperature changes ΔT. Practically, the sensitivity matrix (first term of right side) has a small (relative to the sensitivities) determinant which causes any errors in the frequency measurements to explode. In other words, it constitutes a mathematically stiff problem meaning that for high-resolutions, the frequency shifts must be measured, i.e. the π-shifted FBG resonances must be interrogated, with sufficient accuracy.

3. Interrogation and read-out methods

The two resonances of the PM π-shifted FBG can be interrogated by locking single-frequency lasers to them. The lasers can be frequency stabilized using the Pound-Drever-Hall locking technique [5] which deploys a negative electrical feedback applied to the laser. In this way any optical path length changes of the grating, due to strain or temperature, are translated into changes of the resonant frequency and subsequently alter the output frequency of the laser accordingly.

The read-out system of such a sensor has ideally an output in the electrical domain in order to accommodate both high accuracy frequency measurements and facilitate high read-out speeds. We choose a read-out system based on optical heterodyning. For this a laser with stable output frequency is needed. This reference laser can be mixed individually with the two sensing lasers on two photodetectors. The beating frequencies are then the frequencies v_f and v_s and can be accurately measured using a frequency counter. The sampling rate of the frequency counter can also be used to easily scale the read-out speed of the system.

4. Experimental setup and results

As explained in the previous section the system should consist of three lasers, two sensing and one reference laser, for simultaneously interrogating the two resonances. Here we interrogate the two resonances in succession due to the lack of a third stabilization system by ensuring reproducible conditions for strain and temperature and analyzing the frequency measurements offline.

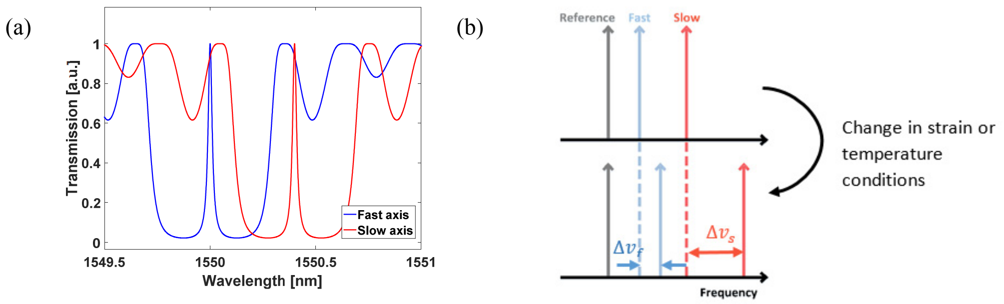

Fig. 1 (a) Illustration of the transmission spectra of a PM π-shifted FBG for the fast- (blue) and slow-axis (red), (b) The fibre birefringence is dependent on strain and temperature therefore the two resonances shift by a slightly different amount.

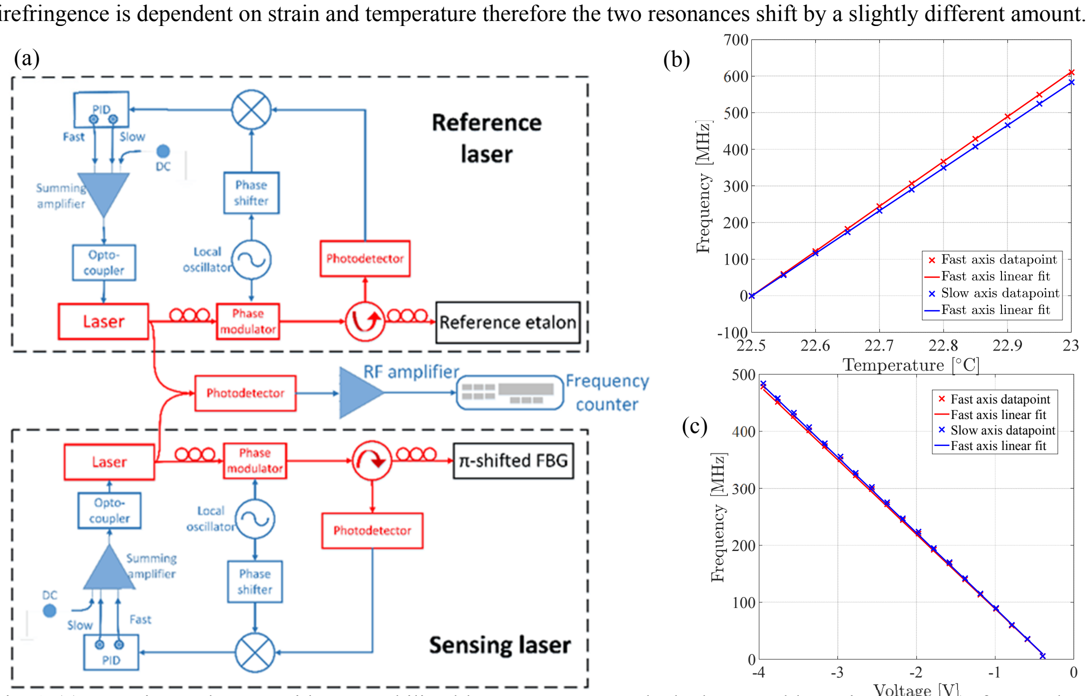

Fig. 2 (a) Experimental setup with two stabilized laser systems, one locked to a stable optical cavity (reference laser), one locked to the π-shifted FBG (sensing laser) and the heterodyne read-out system. The (b) temperature and (c) strain sensitivities for both axes are extracted by linear fitting to the measured frequency shifts as a function of the applied excitation.

A schematic of the experimental setup is shown in Fig. 2(a). The two lasers are multi-section distributed Bragg reflector (DBR) lasers with an intra-cavity ring resonator [6] fabricated with an active-passive InP foundry photonic integration technology [7]. Our lasers have an intrinsic linewidth <100 kHz as shown in [6]. The negative electrical feedback is applied on the reversed biased rear DBR section of the lasers deploying electro-optic and not thermal effects. The stabilization is implemented with a single feedback loop with bandwidth of about 0.5 MHz. The sensing laser is locked to a PM π-shifted FBG with 30 MHz FWHM and the reference laser to a highly-stable Fabry-Perot cavity (<1 MHz/day drift). The grating is mounted on a setup which accurately controls the applied strain and temperature. The strain is applied by a voltage controlled voice coil actuator with a conversion ratio of 1.2 με/V. The two locked lasers are mixed on a photodiode and the frequency of the beat-signal at the output of the photodiode is measured using a frequency counter.

First we extract the fibre strain and temperature sensitivities for both axes by keeping the temperature and strain constant respectively and measuring the beat frequency. The measured frequency shifts are fitted to a linear function shown in Fig. 2(b) and (c). The slope errors from our fittings are ~0.1%. For the system validation we choose to keep the temperature constant and vary the strain. We perform in succession the measurements for the two axes with 10 kHz sampling rate of the frequency counter and solve the system in (1). Some averaging is performed to further increase frequency measurement accuracy, leading to 2.5 Hz read-out speed. The strain measured (red) from our sensing system is shown in Fig. 3(a) with the set strain (blue). The strain residues, i.e. the difference between set and measured strain are shown in Fig. 3(b). The temperature residues which should be around 0 mK and below 1 mK which is temperature control accuracy are shown in Fig. 3(c). The errorbars indicate the estimated resolution of the sensing system based on the standard deviation of the measured points. For the vast majority of the residue points, the zero falls within the errorbars for both strain and temperature. The calculated resolutions are 5.5 nε and 0.38 mK at 2.5 Hz read-out speed. Furthermore our analysis shows that the sensing system resolution is currently limited due to mechanical vibrations because the measurements are taken in series and not simultaneously. We expect a factor of 5 improvement if measurements are taken simultaneously as in a realistic scenario.

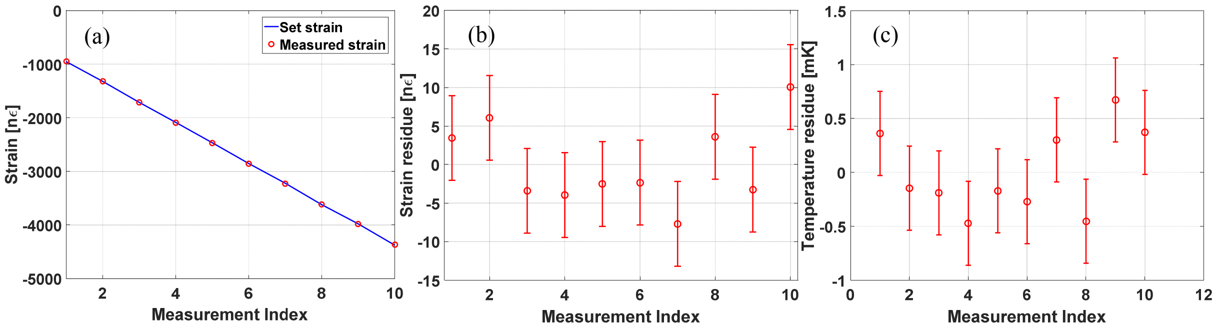

Fig. 3 (a) Applied and calculated strain with constant temperature, (a) Strain and (b) temperature residues. The error-bars indicate the (b) strain and (c) temperature resolutions of the system which are 5.5 nε and 0.39 mK respectively.

5. Conclusions

We demonstrate a fibre-based sensing system for discrimination of strain and temperature with resolutions 5.5 nε and 0.38 mK at 2.5 Hz read-out speed. These are the best resolutions to the best of our knowledge for such a system. We expect further resolution by a factor of five if we extend the system to perform simultaneous measurements.

Acknowledgments

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