Simultaneous Measurement of Displacement and Temperature Using a Low Finesse Cavity and a Fiber Bragg Grating

L. A. Ferreira, A. B. Lobo Ribeiro, J. L. Santos, and F. Farahi

***Abstract*—An optical sensor capable of simultaneously measuring displacement and temperature is presented. It incorporates a fiber Bragg grating temperature sensor and a low-finesse extrinsic Fabry–Perot cavity. A white light tandem interferometric technique is used to recover signal from the low finesse cavity. Signals obtained from the interferometer and the Bragg grating provide required information to simultaneously determine temperature and displacement. Experimental results are presented which demonstrate the feasibility of this sensor topology in practical applications.**

IN FIBER-OPTIC SENSING, the utilization of a low finesse cavity as the sensing element has been shown to be an attractive solution for monitoring several physical measurands in situations when a small sensor is required and the measurements are made at remote locations [1], [2]. An extrinsic low finesse cavity with its simple design and small dimensions meets these requirements. However, in many applications where the primary measurand is displacement, undesirable temperature sensitivity can compromise its operation. This effect can, to some extend, be minimized by using materials with low thermal expansion for the Fabry–Perot cavity [3]. However, a more attractive solution would be a sensor topology that monitors temperature while measuring displacement and hence simultaneously obtain two information [4]. The advantages of this approach are evident, namely, to reduce the constraints on the fabrication of the external cavity, and to measure the local temperature which is very important in many applications.

The subject of simultaneous measurement of several quasi-static parameters has been an active research topic in the past few years [5], [6] and with the advent of fiber Bragg grating this research area has become even more attractive [7]. In particular, fiber Bragg grating sensors have been developed to measure strain and temperature for use in civil structures and composites [8]–[10].

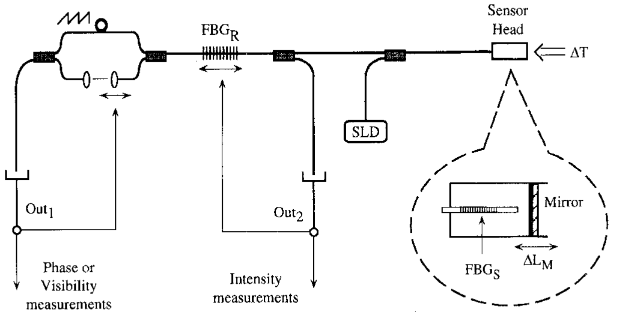

Fig. 1. Proposed sensing system.

In this work, we use a sensor topology which uses a combined fiber Bragg grating and a low finesse cavity. The fiber Bragg grating provides a localized temperature reference for a cavity designed as a displacement sensor, being, however, intrinsically sensitive to temperature as well.

The sensing system is shown in Fig. 1. A cavity length of $\approx$100 μm was formed between the fiber end and a mirror (see inset figure). The low reflection coefficient ($\approx$4%) from the fiber end due to the mismatch of index of refraction between air and glass makes this cavity a low finesse, similar to a two beam interferometer. The cavity length, $L_{\rm CAV}$, was much larger than $L_C \approx 20$ μm, the coherence length of the light source (Superlum SLD-361/A, $\lambda_{\rm peak} = 831$ nm, $\Delta\lambda = 25$ nm, $P_{\rm in\,fiber} = 0.75$ mW). An in-fiber Bragg grating was formed very near to the fiber end, being encapsulated with the Fabry–Perot cavity and fixed to the mechanical structure just in one side to ensure that no strain was applied to it. In this configuration, the grating (FBG$_S$, $\lambda_B = 836$ nm, $\delta\lambda \approx$ 0.2 nm, reflectivity $\approx$90%) is only affected by temperature change within the cavity. Optical signals from the extrinsic Fabry–Perot and from the fiber Bragg grating travel back to the detector via the same optical fiber. The interferometric signal is affected by temperature variations (ΔT) in the cavity and the mirror displacement (ΔL_M) while the spectrum of reflected light from the Bragg grating is only a function of temperature. In the receiving end, a fiber Bragg grating (FBG$_R$, $\lambda_B = 836$ nm, $\delta\lambda \approx 0.2$ nm, reflectivity $\approx$90%) was used in series with a fiber Mach–Zehnder interferometer with an adjustable

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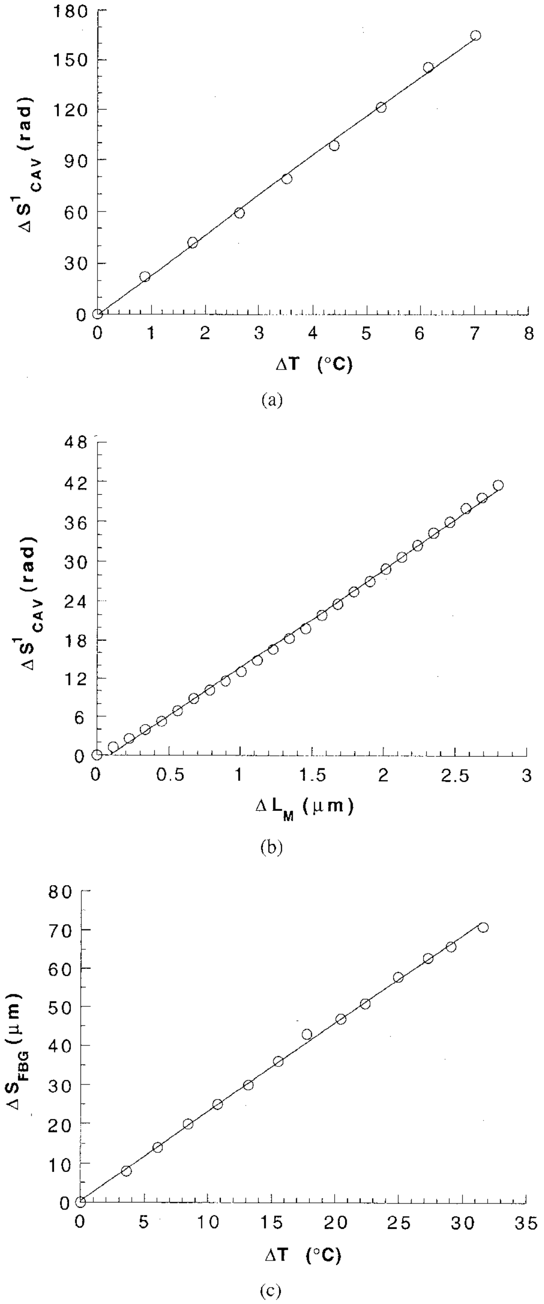
path imbalance. The receiving grating (FBG_R) was actively tuned, via a longitudinal stretch of fiber, to match its spectral response to that of sensing grating (FBG_S). This applied signal is directly proportional to temperature change at the sensor location. Use of gratings with high reflectivities and active tuning techniques are very important in order to prevent light within the spectrum of the gratings from reaching the Fabry–Perot cavity and the receiving interferometer. This will eliminate the cross-talk and reduces noise. The path imbalance of the Mach–Zehnder was adjusted to match with the length of external cavity. Hence, recovery of interferometer signal was achieved using a white light tandem interferometric technique. The system possesses all advantages of a white light interferometer for quasi-static measurement such as, large dynamic range, absolute measurement, and an intrinsic reference when the system is powered ON. A piezoelectric transducer (PZT) was incorporated in one arm of Mach–Zehnder interferometer as a phase modulator. By applying a sawtooth waveform to the PZT, a pseudoheterodyne carrier was generated at the output of the tandem interferometers. The phase sensitivity of the interferometer to applied voltage to the PZT was $K_{\text{PZT}} = 0.23$ rad/V.

The following two equations describe the relation between temperature change and displacement versus interferometric signal and the thermal response of the fiber grating sensor

$$\begin{cases} \Delta S^i_{\text{CAV}} = K^i_{T/\text{CAV}} \cdot \Delta T + K^i_{L/\text{CAV}} \cdot \Delta L_M \quad i = 1, 2 & (1) \\ \Delta S_{\text{FBG}} = K_{T/\text{FBG}} \cdot \Delta T. & (2) \end{cases}$$

In these equations, indices 1 and 2 refer to the two measurement techniques used for recovery of interferometric signal. One is based on phase tracking technique using a pseudoheterodyne carrier (ΔS^1_{CAV} is a phase change); in the other, ΔS^2_{CAV} is the change in length of Fabry–Perot cavity that is measured by continuous monitoring of fringe visibility. In obtaining (1) and (2), we have assumed that the response of this sensor to temperature and displacement is linear within the measurement range.

The coefficients K in (1) were experimentally determined by measuring the interferometric phase (or path imbalance) under these two conditions: 1) the temperature of the cavity was varied while no external displacement was applied to the cavity mirror; 2) the temperature was kept constant while the mirror was displaced. As it is indicated in Fig. 1, the FBG_R was tuned to FBG_S by maximizing the signal at OUT_2. This process yields ΔS_{FBG}. Signal at OUT_1 was either directed to a lock-in amplifier to measure phase or was used to measure fringe visibility. Having measured either phase or visibility, ΔS^i_{CAV} could be obtained. However, the measurement resolution is higher when phase information is used.



(a)

(b)

(c)

Fig. 2. Experimental results. (a) Temperature induced phase changes with no applied displacement to the cavity mirror. (b) Displacement induced phase changes with sensor constant temperature. (c) Elongation of the fiber containing the FBG_R required to keep it tuned to the FBG_S when the sensor temperature changes.

The results presented in Fig. 2(a)–(c) shows a linear response to temperature change and displacement for the cavity and a linear response to temperature change for the Bragg sensor (data in Fig. 2(c) give a Bragg wavelength shift of ≈8.1 pm/°C). This linear behavior supports our initial assumptions that led to (1) and (2). A pseudoheterodyne technique was used to measure the interferometric phase and to obtain data shown in Fig. 2(a) and (b). From these experimental data, the displacement and thermal coefficients of the cavity and thermal coefficient of fiber grating were calculated as

$$\begin{aligned} K^1_{T/\text{CAV}} &= 23.40 \pm 0.37 \text{ rad/°C} \\ K^1_{L/\text{CAV}} &= 15.04 \pm 0.13 \text{ rad/}\mu\text{m} \\ K_{T/\text{FBG}} &= 2.274 \pm 2.4 \times 10^{-2}\ \mu\text{m/°C} \end{aligned} \quad . \tag{3}$$

Substitute these coefficients in (1) and (2), and take the inverse of coefficients matrix to obtain the following equation

$$\begin{bmatrix}\Delta T\\ \Delta L_M\end{bmatrix}=\begin{bmatrix}0 & 0.44\\ 6.6\times 10^{-2} & -0.68\end{bmatrix}\begin{bmatrix}\Delta S^1_{\text{CAV}}\\ \Delta S_{\text{FBG}}\end{bmatrix}. \qquad (4)$$

This simple and attractive form was achieved since the coefficients matrix that generates (1) and (2) is well conditioned with a determinant of ≈34 μm·rad/°C^2.

To assess the validity of (4), we simultaneously changed the temperature of the sensor by 5.1 °C and displaced the mirror by 1.34 μm. The temperature and displacement were then measured with our sensor using (4) as $\Delta T = 5.3$ °C and $\Delta L_M = 1.23$ μm. This corresponds to a deviation of ≈4% for temperature and ≈8% for displacement from the actual values. These results indicate that the proposed sensors can be used to discriminate the effects of temperature and displacement in the cavity. The measurement errors were caused primarily by temperature effect on the Mach–Zehnder interferometer and the receiving grating (FBG_R).

The static sensitivities of the cavity to displacement and temperature were evaluated, ≈0.7 nm/$\sqrt{\text{Hz}}$ and $\approx 4.3\times 10^{-4}$ °C/$\sqrt{\text{Hz}}$, using the pseudoheterodyne processing. The dynamic sensitivity of the sensor was evaluated by applying a signal with an amplitude of 4.4 nm at 20 Hz to the cavity mirror via a PZT. The resulting signal-to-noise ratio was ≈43 dB for a bandwidth of 0.5 Hz. This yields a dynamic displacement sensitivity of ≈0.04 nm/$\sqrt{\text{Hz}}$.

The experiments were repeated, however, this time the visibility of the interference signal was measured rather than the phase. This method, although less sensitive, is much simpler to implement. The following equation was obtained for this set of experiments

$$\begin{bmatrix}\Delta T\\ \Delta L_M\end{bmatrix}=\begin{bmatrix}0 & 0.44\\ 0.50 & -0.67\end{bmatrix}\begin{bmatrix}\Delta S^2_{\text{CAV}}\\ \Delta S_{\text{FBG}}\end{bmatrix}. \qquad (5)$$

Again, these results were tested by simultaneously changing temperature of the sensor by 16.2 °C and displacing the mirror by 20.3 μm. The temperature change of $\Delta T = 17.2$ °C and displacement of $\Delta L_M = 21.0$ μm were measured by the sensor using (5), resulting in errors of ≈6% and ≈3%, respectively.

It is, of course, preferable to make a combined use of fringe visibility and phase measurement in order to obtain a large dynamic range and the highest sensitivity [11]. But, we should emphasise that the measurement accuracy is limited in large by the following:

1) the thermal stability of the receiving interferometer and grating;
2) the accuracy in which coefficients K in (1) and (2) were determined initially;
3) the cross-talk between interferometric signal and signal from grating if the gratings have reflectivity below the ideal value of 100%.

Presently, research works are underway to study the effect of cross-talk as a limiting factor in optimising the system performance.

In conclusion, we presented a new sensor design based on white light interferometry and fiber Bragg grating that allows simultaneous measurement of temperature and displacement. The sensor uses an embedded fiber Bragg grating and an extrinsic Fabry–Perot cavity. The Fabry–Perot cavity has a high displacement resolution and the grating measures the local temperature and therefore provides a reference to compensate for the thermal sensitivity of the cavity. The experimental results demonstrated that this sensor design is highly practical and even with a very simple signal processing method, fringe visibility measurement, the system performance is acceptable for many applications.

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