Low coherence fiber optic system for remote sensors illuminated by a 1.3 μm multimode laser diode

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A fiber optic sensor probe, with two low-finesse Fabry–Perot cavities enabling the determination of displacement (in the range of a typical diaphragm pressure sensor) and temperature, is described. The sensors are connected in a reflective array network and their status is read using coherence tuned sensing based upon a multimode laser diode at 1.3 μm wavelength. Data are presented which show the resolution and linearity of the sensors for the measurement of displacement and temperature.

I. INTRODUCTION

Fiber optic Fabry–Perot sensors are being widely researched because they are highly sensitive to temperature, mechanical vibration, acoustic waves, magnetic fields, etc.[1] Techniques to produce the Fabry–Perot cavities have been described in the literature, using air-glass interfaces at the fiber ends as the reflectors,[2] semireflective splices in a continuous length of fiber,[3] birefringent quartz-crystal cavities,[4] or glass plates with partial reflective coatings,[5] and remote spherical mirrors.[6] For pressure measurements over a wider temperature range, the requirement for a small sensor head, in order to minimize the temperature cross sensitivity, is of paramount importance, and can be fulfilled using a low-finesse Fabry–Perot interferometer with a short optical cavity. Ideally, the cavity length should be two to three times the diaphragm displacement to minimise the temperature cross sensitivity of the sensor. The interrogation of short optical cavities is extremely difficult particularly with laser sources as pseudoheterodyne techniques which require cavity lengths of 2–3 cm (Ref. 7) cannot be used. Recently, new schemes to interrogate very short Fabry–Perot cavity sensors have been demonstrated based upon a dual cavity arrangement.[8,9] Although displacement resolutions of better than 1 nm/$\sqrt{\text{Hz}}$ can be obtained by these methods they are not particularly well suited for quasi-steady-state measurands as the "fringe number" is not readily determined on powering up. In principle the fringe number could be recovered using classical interferometric methods such as illuminating the system with two wavelengths. Another problem arises with the Fabry–Perot in that unavoidable errors occur when its output is demodulated using techniques appropriate for two beam interferometers such as the Michelson.[10] For these reasons we chose to recover the induced phase changes in the interferometer using low coherence (or "white light") techniques, based on the combination of a remote sensor operating in conjunction with a receiving interferometer.

The sensor probe consisted of a low-finesse Fabry–Perot sensor simulator, for displacements in the range comparable to the anticipated movement of a diaphragm pressure sensor used in "bore-hole" measurements and a temperature sensor based upon a miniature Fabry–Perot type cavity. The temperature sensor was included in order that corrections could be applied to the measured displacement (pressure simulator) to correct for any thermally induced dimensional changes. As the fully engineered version of the system is aimed at applications where the distance between the optical processing unit and the sensors is very large (up to 10 km) it is necessary to operate at a communications wavelength, i.e., 1.3 or 1.5 μm with monomode fiber transceiver links, as the fiber attenuation at these wavelengths is small, typically less than 0.5 dB/km.

Although the fiber loss is small, significant losses are incurred at the sensors as the guided beams are ejected from the fiber, reflected from external mirrors, and reinjected back into the fibers. The range of suitably powerful sources exhibiting the required coherence properties is small, a powerful super radiant diode would probably have been the optimum choice however these devices at 1.3 μm are very expensive and have a reputation for very short operational lifetimes. We therefore chose to illuminate the system with a multimode laser diode exploiting the properties of its autocorrelation function which allows it to be used as a source for low coherence sensor systems provided certain criteria are met.[11] These criteria require that the optical path-length imbalance of the sensing and receiving interferometer are equal and correspond to one of the regions in the autocorrelation function of the source where the visibility is very low, i.e., in the region between two successive interference peaks.

The use of low coherence techniques enables the sensors to have a large unambiguous dynamic range and supports sensor self-initialization,[11] when combined with time division multiplexing, it allows the sensors to have the similar path-length imbalances with the same dynamic range. This is a very important advantage because it permits uniformity of the sensor sensitivities and minimizes the level of phase noise present in the system.[12] In the work presented here the autocorrelation function of the 1.3 μm multimode laser diode source was initially measured in order

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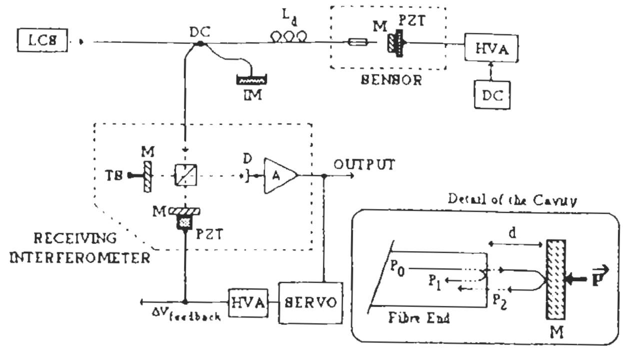

FIG. 1. "White-light" system with a low-finesse Fabry–Perot sensor and a bulk Michelson receiving interferometer with a tracking servo system. Ld: Lead fiber; HVA: high-voltage amplifier; D: photodetector; LCS: low coherence source; DC: directional fiber coupler; M: mirror; IM: index matching gel; TS: translation stage; Ob: microscope objective.

to determine the path-length imbalance for the Fabry–Perot cavities. The results of an experiment, where the sensors were used to measure displacement (simulating the effect of differential pressure) and temperature with their status read using coherence sensing, are then described. The corresponding sensitivities of each sensor were also determined.

II. EXPERIMENTAL SYSTEM

The light source used was a multimode laser diode (HLP 5400 from Hitachi), with a lasing wavelength of 1318 nm, and 3 mW output power (laser biased at 20 mA above threshold, $I_{th}=16$ mA). To measure the autocorrelation function of the laser, i.e., the visibility function, a variable path-length bulk Michelson interferometer, with piezoelectric (PZT) modulator mounted mirror was used.[12] The experimental arrangement used for calibration and characterization of the sensor simulators is shown in Fig. 1. The multimode laser diode was operated cw with an injection current of 28 mA, emitting an average power of 1.3 mW. Figure 2 shows a schematic diagram of the sensor simulator based upon low-finesse Fabry–Perot cavities. The mode of operation of both simulators is essentially the same in that the cleaved distal end of the fiber acts as one of the mirrors of the Fabry–Perot. The fibers are then positioned by means of a mechanical support such that its axis is normal to the measurand driven mirror which forms

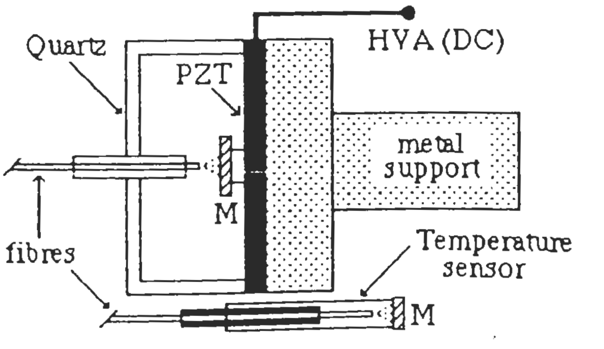

FIG. 2. Scheme of the sensor probe, showing the displacement (pressure) and temperature sensors based upon low-finesse Fabry–Perots.

the Fabry Perot. The cavity lengths (d) of both simulators were set at ~ 620 μm in order that the sensor–receiving interferometer combination was operating in the first low visibility region of the laser diode autocorrelation function.

To simulate the movement of a pressure diaphragm, we used a PZT disc with a silvered planar glass mirror attached, producing a linear displacement equivalent to that of a thin diaphragm under the action of uniformly applied differential pressure. The PZT had a voltage to expansion coefficient of 0.43 rad/V at 500 Hz. The temperature sensor simulator was similar with the mirror mounted on an aluminum tube such that a change in the local temperature caused the distance between the fiber end and the mirror to change.

The calibration of the cavity length was performed with the fiber attached to a translation stage. By tuning the path-length imbalance of the receiving interferometer to be equal to the path-length imbalance of the low-finesse Fabry–Perot cavity, the interference pattern at the output of the receiving interferometer was found to have a visibility of 0.38. The optical power at the output of the system was 0.4 μW. The detector used at the output of the receiving interferometer was a PIN photodiode (PD 7005 from Mitsubishi) with two amplification stages, giving an overall response of 6.9×10^5 V/W, with a -3 dB bandwidth of $\sim$2.3 MHz. The length of the transceiver fiber (L_d) was 1.2 km, and the fiber coupler had a nominal coupling ratio of 50%. After tuning the sensor, a servo system with a bandwidth of 80 Hz and a high-voltage amplifier (HVA) with a gain of 136 were used to lock the combined sensor plus receiving interferometer to one of the first quadrature points of the transfer function. When the servo loop was used in the low bandwidth option, the ratio of phase change versus feedback voltage variation ($\Delta V_{\text{feedback}}$) was measured to be 0.52 rad/V (in quadrature).

III. RESULTS

Figure 3 shows the normalized fringe visibility of the HLP5400 laser diode, measured with a variable path-length bulk Michelson interferometer. Figure 3(a) is for cw operation, with the laser diode running 15 mA above threshold, and Fig. 3(b) gives the visibility variation in the close to zero path imbalance for both the laser diode operating cw and modulated (6 MHz square wave, laser biased at threshold, and injection current amplitude of 15 mA).

Using the low-finesse Fabry–Perot sensors illuminated by the laser source, the fringe visibility at the output of the system was found to be 0.38 (the maximum possible value is 0.5). The mirror (M) in the cavity was translated by applying a high-voltage dc signal to the PZT disk, and the receiving interferometer was maintained in quadrature, coherently tuned to the cavity; Fig. 4(a) shows the corresponding variation of feedback voltage against the mirror displacement and Fig. 4(b) shows an enlarged region of the the data presented in 4(a) over the range 0–0.2 μm, indicating the nanometer resolution of the system. With the system tuned to the temperature sensor, the probe was placed inside a furnace, the temperature of which was

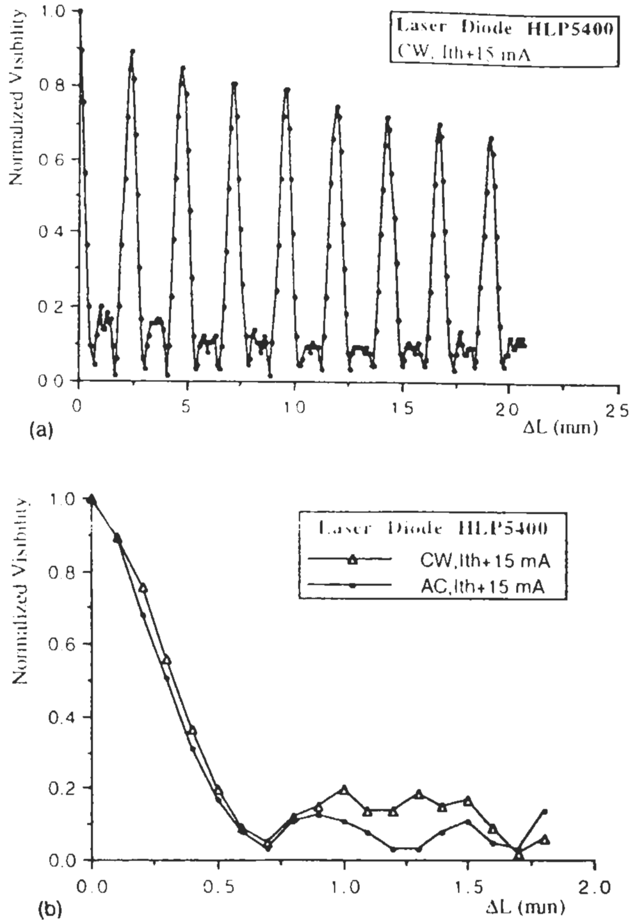

FIG. 3. Fringe visibility vs optical path-length imbalance (a) for the laser operating cw, with an injection current 15 mA, above the laser threshold current (I_{th}). (b) central area of the visibility function (data normalized to its value at $\Delta L=0$), where for cw operation the laser current is the same as for (a). In the ac mode a square wave pulse with a peak current of 15 mA at 6 MHz is superimposed on I_{th}.

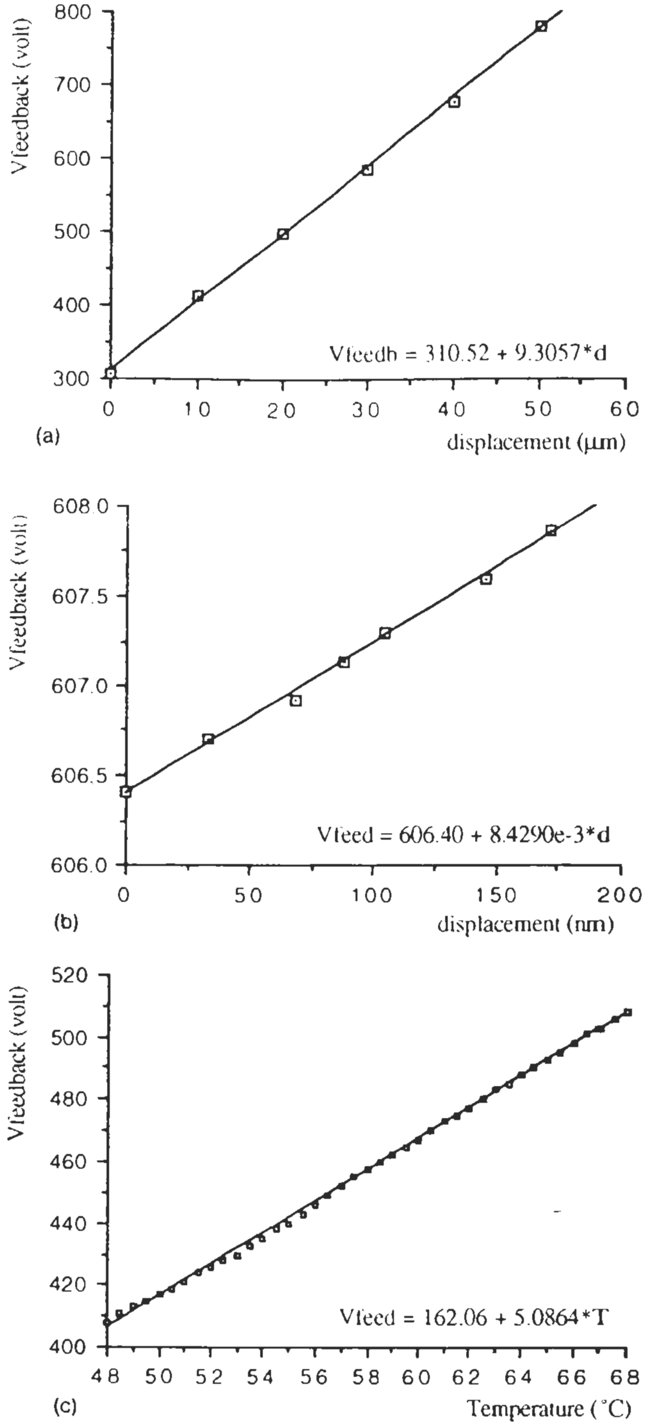

FIG. 4. (a) Feedback voltage vs displacement, induced by the dc voltage applied to the PZT disk, (b) a section of (a) showing the full resolution of the system, (c) feedback voltage vs temperature variation.

monitored with a thermocouple [Fig. 4(c) shows the results]. In order to evaluate the minimum phase resolution of the system (Fig. 5), a small optical phase signal (amplitude: 140 mrad; frequency: 260 Hz) was applied to the PZT disk in the cavity.

IV. DISCUSSION

Figure 3(a) shows the peaked structure of the visibility function typical of multimode laser illumination. The peak separation is ~2.4 mm, which gives a longitudinal laser mode separation of ~130 GHz. From Fig. 3(b), the width at half-height (W) for the central region is W (cw; $I_{th}+15$ mA) ~334 μm and W (ac; $I_{th}\pm 15$ mA) ~298 μm. The optical path-length imbalance of the interferometers must then be around 550 μm, in order to obey the "white light" condition.[12] As can be seen, for the case of the laser diode modulated with a 6 MHz square wave, biased at threshold with an injection current of 15 mA, the visibility function did not change significantly.

From Fig. 5 the measured sensitivity (for a signal-to-noise ratio of one and with the system in quadrature) was found to be 0.8 mrad/$\sqrt{\text{Hz}}$. The corresponding sensitivities of the two low-finesse Fabry–Perot cavities were 1.65×10^{-10} m/$\sqrt{\text{Hz}}$ for displacement, and 3.4×10^{-6} K m/$\sqrt{\text{Hz}}$ (K m/$\sqrt{\text{Hz}}$) for temperature. The data presented here were taken by sequentially manually tuning each sensor to the quadrature point before the servo was locked.

In order to realize a practical version of this system it will be necessary to (1) incorporate a technique which will automatically identify a fiducial point in the transfer function of the combined sensor receiving interferometer pair and (2) combine it with a method which will allow the two sensors to be multiplexed. Various techniques have been

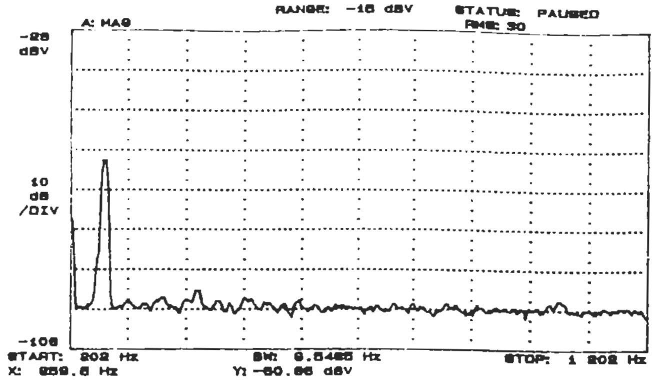

FIG. 5. Spectrum of the photodiode current in the range 202–1202 Hz showing the output of the system when a test signal of 140 mrad (peak amplitude) was applied to the low-finesse cavity mirror.

described in the literature for determining the fiducial point in the autocorrelation function; for example, the optical path difference (OPD) of the receiving interferometer is scanned and the output signal is stored in a computer[13] together with the corresponding values of the OPDs. The centroid of the autocorrelation function of the combined interferometers can then be determined with a suitable computer program. The accuracy depends mainly on the precision of the tracking stage in the receiving interferometer. One of the problems is the time required to perform the calculations. An alternative approach which requires significantly less time is to determine the fiducial point with dedicated hardware as reported by Gerges,[14] the resolution achieved was 0.26 mrad/$\sqrt{\text{Hz}}$.

Various multiplexing schemes for fiber optic sensors have also been reported in the literature of which time division is the most appropriate in the present context. As indicated in Fig. 3(b), time division multiplexing (TDM) can be implemented directly by pulsing the laser as the source autocorrelation function is virtually unaffected by this type of modulation. With up to 8 sensors in a TDM network, minimum sensitivities of 15–20 μrad/$\sqrt{\text{Hz}}$ have been reported.[15] This noise is primarily due to laser phase noise caused by the finite path imbalance (2–3 cm) of the sensors, required for signal recovery based upon single-mode laser diodes. For the system reported here, the effective path length is less than 1 μm, therefore phase noise will not limit the performance, and as we only require a modest phase sensitivity of 10^{-3} rad to achieve a range to resolution of 10^5:1 for a tracking range of 100 μm, the additional noise associated with multiplexing only two sensors should not be important. TDM will be achieved inserting a fiber delay line (L_d) at the second output port of the coupler in Fig. 1, pulse modulating the optical source with a proper mark space ratio, and using an electronic two channel demultiplexer after the amplification stage (which will be driven synchronously by the laser diode switching pulse). A piezoelectric transducer of the type available from Queensgate Instruments with a resolution of $>10^{-9}$ m Hz (m Hz) and a tracking range of 100 μm would provide adequate performance for the tracking unit in the receiving interferometer. The signal demodulation can be performed using two parallel receiving interferometers or, alternatively, one single receiving unit with some type of switching that connects sequentially which one of the sensors.

A fully engineered pressure sensor based upon the design shown in Fig. 2 with accurate thermal compensation provided by the temperature sensor would offer comparable performance to commercial "oil-well" logging pressure sensors on the market.[16] As the fiber loss at 1.3 μm is so small, the practical operational range for the system exceeds 10 km with an anticipated "update rate" compatible with the normal "loggin" requirements of a typical oil well.

In conclusion, we have demonstrated a sensor probe incorporating dual Fabry–Perot sensors with the potential to be developed into a temperature compensated precision pressure probe for truly remote operations.

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