Simultaneous Measurement of Temperature and Strain: Cross-Sensitivity Considerations

FARAMARZ FARAHI, DAVID J. WEBB, JULIAN D. C. JONES, AND DAVID A. JACKSON

Abstract—Interferometric sensors using optical fibers as a transduction medium have been shown to be sensitive to a variety of physical measurands. A result of this is that the resolution of a system designed to sense strain, for example, may be compromised by fluctuations in the temperature of the environment. We discuss the possibility of simultaneously determining the strain and temperature applied to the same piece of highly birefringent fiber. Second-order effects are shown to be important for long sensing lengths or in the presence of high strains or temperature changes. We also describe the results of experiments carried out to verify our theoretical predictions.

I. Introduction

MANY optical fiber interferometric temperature and strain sensors possessing very high resolutions have been reported [1]–[3]. The great resolution of these sensors is due to the sensitivity of the optical path, and therefore the optical phase, to various physical quantities. Because the optical path is sensitive to several different stimuli, it is difficult to make the sensor specific. For example, an interferometric strain gauge shows serious cross sensitivity to temperature. Furthermore, the transfer function of an interferometer is periodic, so that the unambiguous measurement range generally corresponds to a phase change of 2π rad. Several methods to increase the measurement range of interferometric sensors have been reported. In the dual wavelength technique, two sources with different wavelengths (λ_1, λ_2) simultaneously illuminate the system. The difference between the phases of the outputs corresponding to λ_1 and λ_2 is a phase equivalent to that which would be produced if the interferometer were illuminated by a source of wavelength $\lambda_1\lambda_2/(\lambda_1 - \lambda_2)$, hence extending the measurement range of the system [4]. Simultaneous recovery of phase and polarization information in interferometers made from birefringent components have been reported in which the high resolution of the interferometric sensor is combined with the larger measurement range of the polarimetric sensor [5], [6]. The last technique has been applied to the all-fiber system, where the two polarization modes of a piece of highly birefringent fiber were used to act as two fiber Fabry–Perot cavities [7], [8]. Two interferometric outputs were observed, and the polarization information was extracted from the differential phase between the two independent interferometric outputs.

Although the unambiguous operating range is enhanced with either of these two techniques, the problem of environmental susceptibility still exists. It is, however, possible to implement a remote interferometric sensor, which is addressed by an environmentally insensitive input lead [9]. However, even in this system, the sensing element remains susceptible to cross sensitivities; for example, if the sensing element simultaneously experiences both axial strain and a temperature change, the resulting interferometric phase change is caused by a combination of both effects, and neither can separately be identified. This cross sensitivity may be removed by using a birefringent interferometer and recovering the phase and polarization information simultaneously, as in the technique just described for the enhancement of measurement range. The basis of the technique is that the ratio of phase to polarization sensitivity is different from temperature and strain. Hence, if both the interferometric phase and polarization state are determined, then by solving two simultaneous equations, the temperature and strain may be found [10]. In [10], experiments in which different sections of a birefringent fiber were heated and strained are described, where the fiber formed part of a polarization interferometer. A length of elliptical core two-mode fiber for simultaneously measuring temperature and strain was used in which the LP_{01} and LP_{11} modes polarized along the core ellipse minor axis interfere at the fiber output and light in the LP_{01} and LP_{11} modes polarized along the core ellipse major axis interfere at the fiber end [11]. Using these two interferometric signals one could simultaneously determine the temperature change and the axial strain present in the fiber. For the same purpose Meltz *et al.* [12] have used twin-core fiber by considering that temperature and strain sensitivities are wavelength dependent. These techniques avoid consideration of second-order effects which may simultaneously affect the resolution of the system when the variations in strain and temperature affect the same portion of the fiber.

In this paper, we consider the effect of heating and straining the same part of a birefringent fiber. We have been able to simultaneously determine the temperature and strain. This technique may be applied, for example, to realize an interferometric strain gauge with inherent temperature compensation. In the course of this work, we in-

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vestigated the interaction between temperature and strain in a birefringent optical fiber. The fiber was configured as a fiber Fabry–Perot interferometer used in reflection.

II. Theory

Following the notation used by Hocker [1] and Butter and Hocker [3], the phase of a light beam traveling inside a fiber with a propagation constant β and length L is

$$\phi_j = \beta_j L, \qquad j = f, s \tag{1}$$

where f and s refer to the fast and slow eigenaxes of the highly birefringent fiber. For an applied temperature change (ΔT), or strain ($\Delta\epsilon$) we have

$$\Delta\phi_{jT} = LK_{jT}^0 \Delta T \tag{2a}$$

or

$$\Delta\phi_{j\epsilon} = LK_{j\epsilon}^0 \Delta\epsilon \tag{2b}$$

where

$$K_{jT}^0 = \frac{1}{L}\left[L\frac{\partial\beta_j}{\partial T} + \beta_j\frac{\partial L}{\partial T}\right]_{\Delta\epsilon = 0} \tag{3a}$$

and

$$K_{j\epsilon}^0 = \frac{1}{L}\left[L\frac{\partial\beta_j}{\partial \epsilon} + \beta_j\frac{\partial L}{\partial \epsilon}\right]_{\Delta T = 0}. \tag{3b}$$

K_{jT} and $K_{j\epsilon}$ are the normalized thermal and strain coefficients of the fiber. If the temperature change and strain are simultaneously applied to the fiber, the total phase change is simply the sum of (2a) and (2b) (ignoring, for the moment, any cross-sensitivity effect), i.e.,

$$\Delta\phi_j = L\left[K_{jT}^0\Delta T + K_{j\epsilon}^0\Delta\epsilon\right], \qquad j = f, s. \tag{4}$$

Equation (4) is in fact a set of two simultaneous equations which can be solved to determine ΔT and $\Delta\epsilon$ from the experimentally determined $\Delta\phi_f$ and $\Delta\phi_s$.

To include the cross-sensitivity effect we consider $\beta(T, \epsilon)$ and $L(T, \epsilon)$ as two analytic functions of temperature and strain. It is then possible to use a Taylor expansion to find their response when a temperature change (ΔT) and strain ($\Delta\epsilon$) are applied simultaneously, i.e.,

$$\begin{aligned}\phi_j = {} & \beta_j(T_0, \epsilon_0)L(T_0, \epsilon_0) + \left[\beta_j\frac{\partial L}{\partial T} + \frac{\partial\beta_j}{\partial T}L\right]^{T=T_0,\epsilon=\epsilon_0}\Delta T \\ & + \left[\beta_j\frac{\partial L}{\partial\epsilon} + L\frac{\partial\beta_j}{\partial\epsilon}\right]^{T=T_0,\epsilon=\epsilon_0}\Delta\epsilon \\ & + \left[\beta_j\frac{\partial^2 L}{\partial T\partial\epsilon} + L\frac{\partial^2\beta_j}{\partial T\partial\epsilon} + \frac{\partial\beta_j}{\partial\epsilon}\cdot\frac{\partial L}{\partial T} + \frac{\partial\beta_j}{\partial T}\cdot\frac{\partial L}{\partial\epsilon}\right]^{T=T_0,\epsilon=\epsilon_0}\Delta\epsilon\Delta T \\ & + \left[\beta_j\frac{\partial^2 L}{\partial T^2} + L\frac{\partial^2\beta_j}{\partial T^2}\right]^{T=T_0,\epsilon=\epsilon_0}(\Delta T)^2 \\ & + \left[\beta_j\frac{\partial^2 L}{\partial\epsilon^2} + L\frac{\partial^2\beta_j}{\partial\epsilon^2}\right]^{T=T_0,\epsilon=\epsilon_0}(\Delta\epsilon)^2 + \cdots.\end{aligned} \tag{5}$$

As is clear from (5), the higher order terms' contribution increases with increasing ΔT and $\Delta\epsilon$. This has been experimentally observed in that for a large temperature variation the phase change with temperature is seen to be nonlinear [13]. In this work we do not consider such large variations and therefore ignore the higher order effects to simplify (5) as

$$\Delta\phi_j = L[K_{jT}^0\Delta T + K_{j\epsilon}^0\Delta\epsilon] + K_{jT\epsilon}^0\Delta\epsilon\Delta T \tag{6}$$

where

$$K_{jT\epsilon}^0 = K_{j\epsilon T}^0 = \left[\beta_j\frac{\partial^2 L}{\partial T\partial\epsilon} + L\frac{\partial^2\beta_j}{\partial T\partial\epsilon} + \frac{\partial\beta_j}{\partial\epsilon}\cdot\frac{\partial L}{\partial T} + \frac{\partial\beta_j}{\partial T}\cdot\frac{\partial L}{\partial\epsilon}\right]^{T=T_0,\epsilon=\epsilon_0} \tag{7}$$

which can be written in the following form:

$$\begin{aligned}K_{jT\epsilon}^0 &= \left[\frac{\partial}{\partial\epsilon}(LK_{jT}^0)\right]^{T=T_0,\epsilon=\epsilon_0} \\ &= K_{jT}^0\left[\frac{\partial L}{\partial\epsilon}\right]^{T=T_0} + L\left[\frac{\partial K_{jT}}{\partial\epsilon}\right]^{\epsilon=\epsilon_0}\end{aligned} \tag{8}$$

For an axial strain we substitute $\Delta\epsilon$ by $\Delta L/L$, and therefore (6) becomes

$$\Delta\phi_j = L[K_{jT}^0\Delta T + K_{jL}^0\Delta L] + K_{jTL}^0\Delta L\Delta T \tag{9}$$

and (8) becomes

$$K_{jTL} = \frac{1}{L}K_{jT\epsilon} = K_{jT} + L\frac{\partial K_{jT}}{\partial L}. \tag{10}$$

The $K_{jTL}\Delta L\Delta T$ term in (9) is the cross-sensitivity term, and it can be seen that the cross sensitivity is a function of sensing length L. Now by measuring the thermal (or strain) coefficient of the sensing element for different applied strains (or temperature), the cross-sensitivity coefficient can be determined. Therefore (9) is a set of two simultaneous equations which can be solved to determine ΔT and ΔL in terms of measurable phase retardances $\Delta\phi_j$.

III. Experiments and Results

The experimental arrangement used is shown in Fig. 1. Linearly polarized light from a single-mode helium–neon laser was launched into the sensing fiber via a half-wave plate ($\lambda/2$) and beamsplitter BS. The half-wave plate was used to rotate the state of polarization of the input beam such that it made an angle of 45° with the fiber eigenaxes, thus equally populating both eigenaxes. Light reflected from the input face and the light reflected from the silvered distal end of the fiber coherently mixed together. This beam was divided by a polarizing beamsplitter PBS, the polarization axes of which were adjusted to coincide with those of the fiber using the second half-wave plate. The two independent outputs thus correspond to the two fiber Fabry–Perot cavities and were monitored using photodiodes PD1 and PD2. A 2.5-m-length fiber was used and was partially wound onto a piezoelectric cylinder to

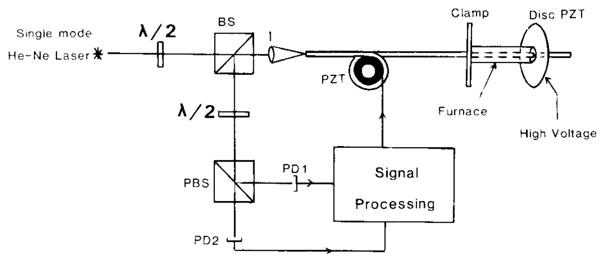

Fig. 1. Experimental arrangement: BS: beamsplitter; PBS: polarizing beamsplitter; $\lambda/2$: half-wave plate; PD: photodiode; l: launching lens (×10): PZT: piezoelectric transducer.

allow phase modulation of the guided beam, thus facilitating the signal processing described below.

In order to demonstrate the simultaneous measurement of strain and temperature, a 7-cm length of the fiber was enclosed in an electrically heated furnace and was clamped at one end while the other end was fixed into a disk piezoelectric transducer. This configuration enabled us to simultaneously apply axial extension and heat to the common sensing element. The system was thermally isolated using a polystyrene box, and the sensing element was also similarly isolated from the remaining fiber.

The signal processing used was a pseudoheterodyne technique, in which a sawtooth voltage was applied to the cylindrical PZT to drive the two interferometers over approximately one period of their transfer functions [14], [15]. Fig. 2(a) and (c) show the two interferometer irradiances. These signals were bandpass filtered at the frequency of the modulation signal to produce two strong sinusoidal carriers free from the distortions in the photodetectors' signals caused by the ramp fly back (Fig. 2(b) and (d)) [14], [15]. These bandpass-filtered photodetectors' signals thus have the familiar form:

$$I_j \propto 1 + K \cos(\omega t + \phi_j) \quad (11)$$

where ω is the angular frequency of the modulation signal and ϕ_j is the phase retardance generated in the jth eigenaxis of the fiber. The sawtooth signal was bandpass filtered to produce the reference carrier at the same frequency ω. The phase of both signal carriers were simultaneously compared with the reference carrier, using two lock-in analyzers.

Using this system the thermal coefficients of the sensing fiber were measured, the temperature and the corresponding phase retardances being simultaneously recorded using a computer. For no axial extension applied, the thermal coefficients were found to be

$$LK_{fT} = 8.681 \pm 0.031 \text{ rad} \cdot {}^\circ\text{C}^{-1}$$
$$LK_{sT} = 8.089 \pm 0.023 \text{ rad} \cdot {}^\circ\text{C}^{-1}. \quad (12)$$

The strain coefficients were measured in a similar way. Great care was taken to avoid errors resulting from temperature changes. The fiber was kept at a constant temperature of 23.5°C, and a range of voltages were applied to the disk piezoelectric transducer (PZT) to produce corresponding axial extensions of the fiber. The voltage and

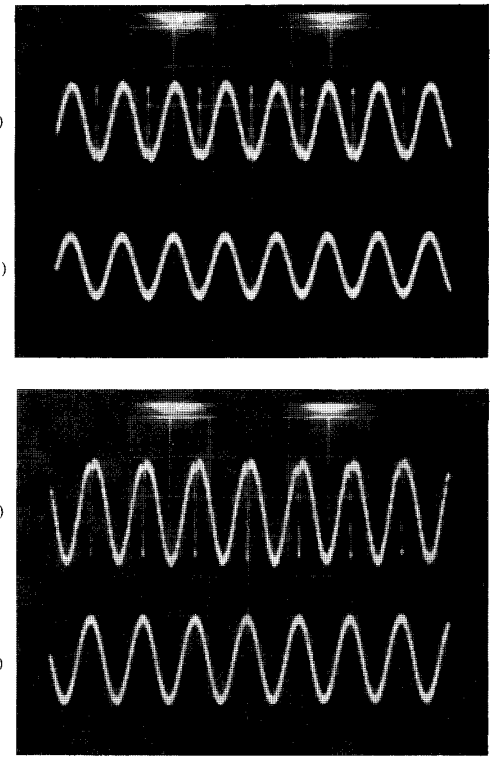

Fig. 2. Two interferometer outputs when the cylindrical PZT is modulated with a ramp voltage. (a) and (c) Distortions in photodetector signals caused by ramp fly back. (b) and (d) Bandpass-filtered signals free from photodetector signal distortions.

the output of the two lock-in analyzers were recorded by a computer. The strain coefficients were measured to be

$$LK_{fL} = 10.601 \pm 0.021 \left[\text{rad} \cdot (\mu\text{m})^{-1}\right]$$
$$LK_{sL} = 10.730 \pm 0.015 \left[\text{rad} \cdot (\mu\text{m})^{-1}\right]. \quad (13)$$

These results were confirmed by applying a small 70-Hz sinusoidal strain signal to the disk PZT while the interferometers were driven over one period of their transfer function by a ramp voltage (at 1 kHz) applied to the cylindrical PZT. It has been shown that in this case most of the power is concentrated in the first harmonic of the ramp frequency [15]. Therefore, the 70-Hz signal appeared as sideband of the 1-kHz carrier signal. The amplitude of the 70-Hz sideband was measured using a spectrum analyzer. This is proportional to the axial extension at that frequency for small extensions (Fig. 3).

To determine the cross-sensitivity effect, the sensing element was axially stretched in steps, and for each step, the thermal coefficients were measured as explained before. Fig. 4 shows the two thermal coefficients against applied axial extension. Values of

$$K_{fTL} = -0.143 \pm 7 \times 10^{-3} \text{ rad} \cdot {}^\circ\text{C}^{-1} \cdot (\mu\text{m})^{-1}$$
$$K_{sTL} = -0.139 \pm 5 \times 10^{-3} \text{ rad} \cdot {}^\circ\text{C}^{-1} \cdot (\mu\text{m})^{-1} \quad (14)$$

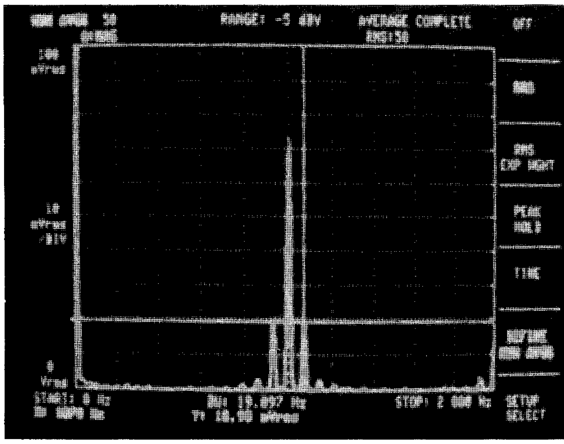

Fig. 3. Signals in frequency domain: 70-Hz strain signal appears as sideband of the 1-kHz carrier signal.

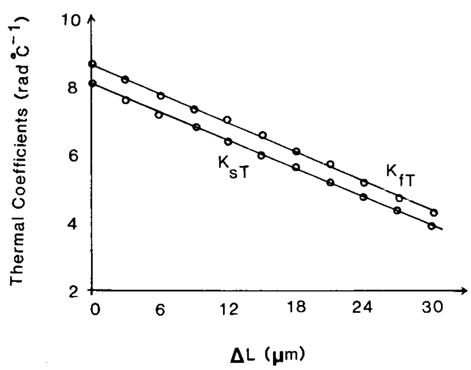

Fig. 4. Thermal coefficients K_{fT} and K_{sT} as functions of fiber axial extension ΔL.

for a 7-cm sensing fiber were measured. These experimentally evaluated coefficients in conjunction with a set of two equations (9) are all the information required to determine ΔL and ΔT for each pair of $\Delta\phi_f$, $\Delta\phi_s$.

IV. Discussion

We have demonstrated an interferometric technique which allows simultaneous measurement of strain and temperature applied to a sensing fiber. The cross-sensitivity effect has been analytically determined and experimentally measured for a 7-cm-length sensing element. It has been shown theoretically that this cross effect is dependent on the sensing length. This effect is therefore of great importance when a very long fiber is required to be used as a strain gauge [16]. This concept and the experimental results were checked by applying various strains to the fiber while it was heated. The results of two methods, with and without cross-sensitivity consideration, were compared. It was shown that for very small temperature change and applied strain the results of two methods are comparable, and the cross-sensitivity effect was only significant for large applied strains or temperature variations. The experimental error was mainly due to the effect of temperature on the PZT and the clamp fixed at the two ends of the sensing element and also to temperature variation communicated to the rest of the fiber. This problem can be solved if one uses a remote configuration where the fiber lead has no sensitivity [17].

The present system has a limited measurement range as both the interferometers outputs have the periodic form (11) with the unambiguous range of 2π rad. This problem can no longer be solved by a combined interferometric–polarimetric system, because the interferometric and polarimetric outputs have already been used in the recovery of the two measurands. The dual wavelength technique [4] is a possible solution although it requires two frequency-stabilized sources. In this case the strain, temperature, and the cross-effect coefficients are not the same for different wavelengths, thus enabling the measurement range to be extended. An alternative solution has recently been demonstrated by Newson *et al.* [18], where a white light technique, in conjunction with a dual interferometer, is used to recover two independent outputs. However, this application requires two local interferometers corresponding to the two sensing interferometers due to the fast and slow eigenaxes of the highly birefringent fiber. For each separate system an electronic servo is required to hold the interferometer in balance [19]. The measurement range of this system is limited by the range of the PZT deployed in the local interferometers. The advantage of the white light technique is that absolute rather than relative measurements are made, so the system can be initialized.

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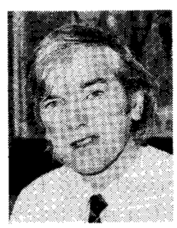

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