Passive Interrogation of Low-Finesse Fabry–Pérot Cavities Using Fiber Bragg Gratings

M. Dahlem, J. L. Santos, L. A. Ferreira, and F. M. Araújo

***Abstract*—An investigation on the application of fiber Bragg gratings for the interrogation of interferometric low-finesse Fabry–Pérot cavities is reported. The proposed scheme is based on the generation of two quadrature phase-shifted signals that allows the recovering of the change in the cavity length. Besides being totally passive, this technique offers a high degree of flexibility and has the potential to be used in the interrogation of very short cavities.**

***Index Terms*—Displacement measurement, Fabry–Pérot cavities, Fiber Bragg gratings, fiber optic sensors, temperature measurement.**

I. Introduction

A LOW-FINESSE Fabry–Pérot interferometer with a short cavity has always been an attractive choice for a high-performance localized sensing element [1]. Its importance becomes more evident in those applications where fiber Bragg gratings (FBG) cannot be used, for example, in the monitoring of displacement. In such cases, a Fabry–Pérot cavity formed between the distal fiber exit and the surface of the displaced object is an obvious solution, being known that the associated transfer function approaches that of a two-beam interferometer [2]. The recovering of the interferometric phase, which contains the information relative to the object displacement (or, more generally, about a particular measurand that acts on the optical path difference (OPD) of the cavity), is not straightforward. There are two main reasons for this: the cavity is electrically passive (considering it is normally placed remotely from the signal processing unit); and the cavity length is usually small (typically it does not exceed a few hundreds of micrometers).

To overcome this problem, two types of approach have been explored to perform the phase recovery operation. One of them relies on the white light concept. In this case, the light returning from a low-finesse Fabry–Pérot cavity and emitted by an optical source with a coherence length smaller than the cavity OPD is processed by a second interferometer located in the processing unit [3], [4]. The other type is based on the generation of quadrature phase-shifted interferometric signals through the utilization of dual-wavelength illumination [5], [6] or dual-length coupled cavities [7], [8]. The consideration of coupled cavities presents not negligible practical constraints, essentially related with the design of the sensing head. On the other hand, dual-wavelength illumination is a conceptually elegant process to interrogate such remote low-finesse Fabry–Pérot cavities. However, considering their small length, it is not a straightforward task to get an optical source able to illuminate the cavity with two wavelengths sufficiently far apart and with proper characteristics in order to generate two interferometric signals that change in quadrature.

In this letter, we propose the utilization of FBGs as spectral discriminators with properties suitable to the interrogation of low-finesse Fabry–Pérot cavities. The scheme reported here relies in the use of proper FBG resonant wavelengths in order to obtain quadrature phase-shifted signals.

II. Theory

The interferometric phase of light reflected from a low-finesse Fabry–Pérot cavity is a well-known function of wavelength. If two distinct wavelength discriminators with bandwidth narrower than the spectral response of the Fabry–Pérot cavity are used to analyze backreflected light, we can write the interferometric phase at each wavelength as

$$\phi_j = \frac{4\pi n L}{\lambda_j}, \quad j = 1, 2 \tag{1}$$

where

n effective refractive index of the Fabry–Pérot cavity;
L length;
$\lambda_{1,2}$ resonances of the two wavelength discriminators.

The relative phase between the two correspondent interferometric signals is given by

$$\Delta\phi = 4\pi n L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right). \tag{2}$$

These signals will be in quadrature when the wavelength separation between the resonant wavelengths is an odd multiple of $\lambda^2/(8nL)$, where the approximation $\lambda_1 = \lambda_2 = \lambda$ was considered. This approximation is valid within 1% of error for cavity lengths higher than ~20 μm. For a given cavity length, it is always possible to define two resonant wavelengths that watch the above condition.

The output voltages v_1 and v_2 at two photodiodes used to measure independently light backreflected at each wavelength are then given by

$$\begin{aligned} v_1 &= V_1(1 + \kappa_1 \cos\phi_1) \\ v_2 &= V_2[1 + \kappa_2 \cos(\phi_1 + \Delta\phi)] \\ &= V_2(1 + \kappa_2 \sin\phi_1) \end{aligned} \tag{3}$$

Manuscript received December 5, 2000; revised June 8, 2001.

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Publisher Item Identifier S 1041-1135(01)07527-9.

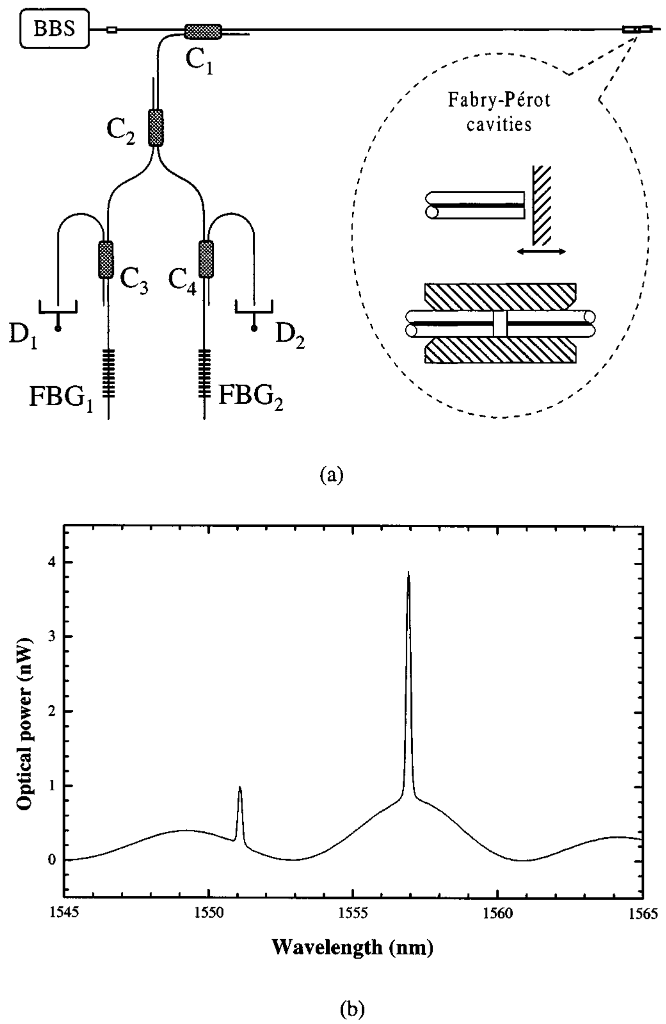

Fig. 1. (a) Experimental setup for generation of quadrature phase-shifted outputs. (b) Spectral responses of the Fabry–Pérot cavity and the Bragg gratings.

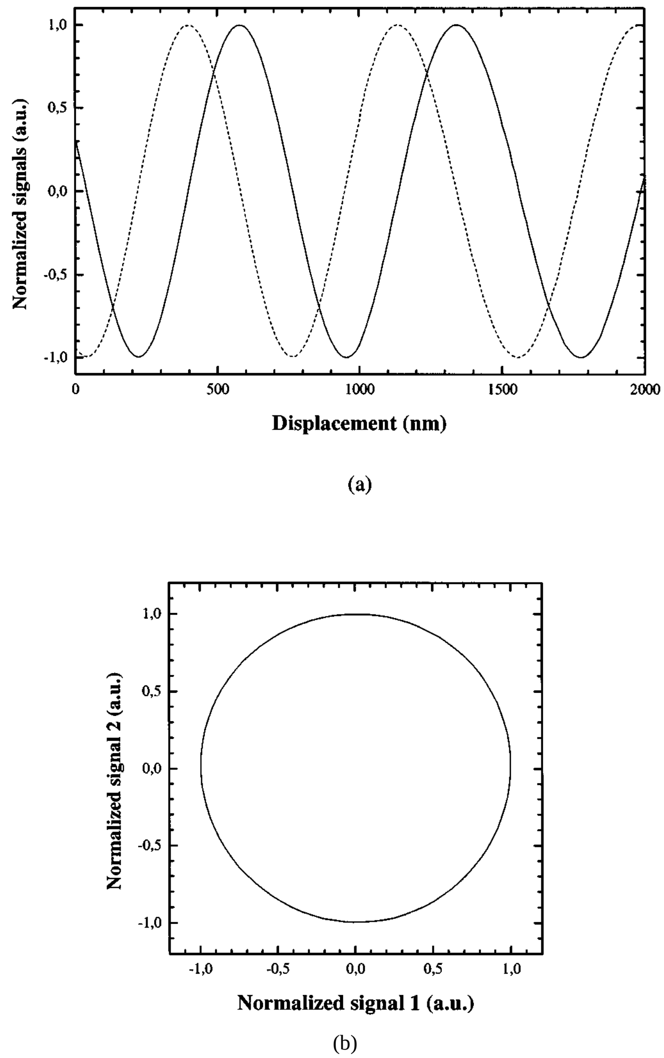

Fig. 2. (a) Output signals versus cavity displacement, and (b) x–y signal representation illustrating the quadrature condition.

where $V_{1,2}$ are constant voltages dependent on the optical power and gain in the detection electronics and $\kappa_{1,2}$ is the fringe visibility at each wavelength.

Proper gain adjustment, i.e., setting $\kappa_1 V_1 = \kappa_2 V_2$, allows the recovering of the interferometric phase through the following relation:

$$\phi \equiv \phi_1 = \tan^{-1}\left(\frac{v_2 - V_2}{v_1 - V_1}\right). \tag{4}$$

The unambiguous phase recovery from $-\pi$ to π can then be computed using the above equation and one of the signals in (3).

III. Experiment and Discussion

The schematic diagram of the experimental configuration is shown in Fig. 1(a). An erbium-doped broad-band light source (with central wavelength ~1550 nm and 10 mW of average optical power) was used to illuminate a Fabry–Pérot cavity through a 50 : 50 coupler (C_1). The cavity was formed in air ($L \approx$ 500 μm) by placing the tip of an optical fiber in front of a mirror coupled to a micropositioning piezoelectric (PZT) translation stage, allowing the cavity length to be controlled [upper inset in Fig. 1(a)]. The interferometric light signal reflected from the cavity was then coupled through C_2 (50 : 50) into two FBG wavelength discriminators. Backreflected light at each resonant wavelength was monitored using two photodiodes and couplers C_3 and C_4 (both 50 : 50); the average optical power reaching each detector was ~5 nW. These signals were then acquired and processed using LabView software. All the remain fiber ends were angled cut to avoid spurious reflections. As referred on the last section, the discriminator wavelengths must be properly selected to ensure that the relative phase between the signals is an odd multiple of $\pi/2$. In this experiment, the chosen resonant wavelengths were $\lambda_{B1} =$ 1551.1 and $\lambda_{B2} =$ 1556.9 nm (~0.2-nm bandwidth). Fine tuning could be achieved by applying strain to one of the Bragg gratings. The quadrature condition is illustrated in Fig. 1(b). This figure was obtained at coupler C_2 by allowing some backreflection of light at the end of the fibers containing the FBGs. It shows the spectrum of the light exiting the Fabry–Pérot cavity and the two FBG resonance signals, indicating a $3\pi/2$ phase difference between the two interferometric signals.

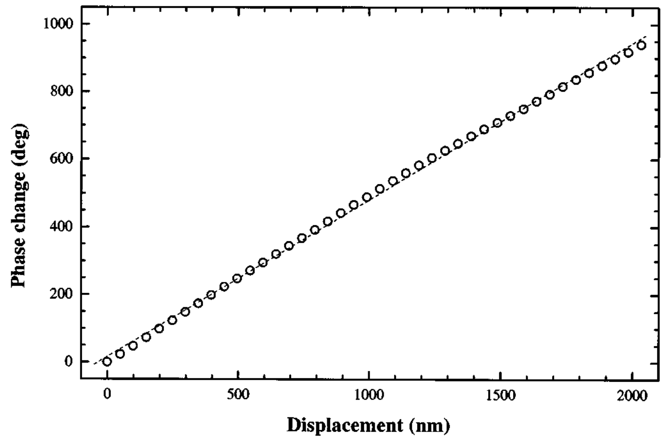

Fig. 3. Phase change versus cavity displacement.

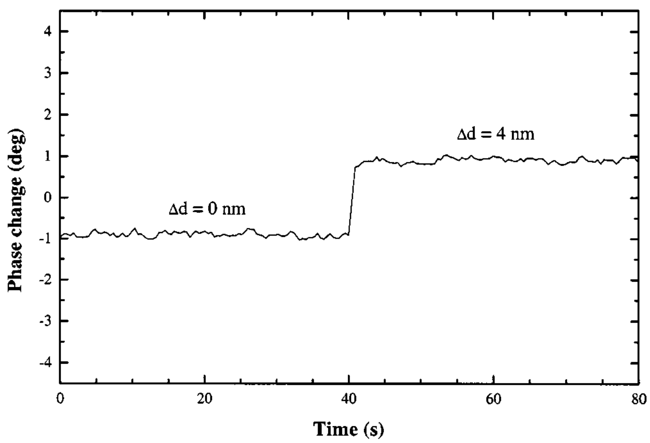

Fig. 4. Displacement sensor resolution.

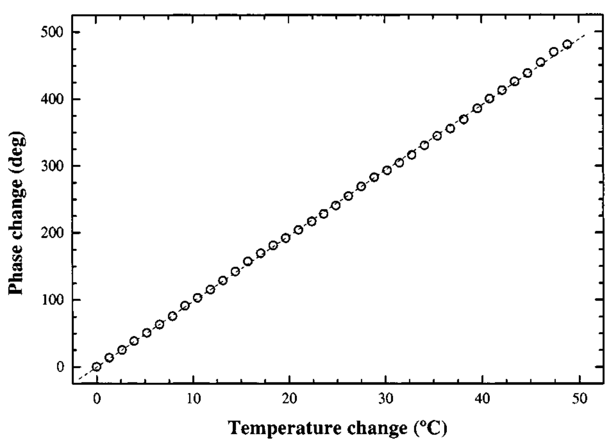

Fig. 5. Phase change versus temperature (second sensing head).

It must be noted that by choosing two discriminators with different resonances it is also possible to satisfy the quadrature condition through adjustment of the cavity length, as long as the respective bandwidths stay narrower than half-period of the channeled spectrum of light reflected by the cavity.

Small displacements were made in the cavity by changing the voltage applied to the PZT. The normalized output voltages obtained from both detectors in this situation are represented in Fig. 2(a). Fig. 2(b) confirms the quadrature phase-shifted relation between these two signals.

The shift in the interferometric phase as a function of the cavity length variation is shown in Fig. 3. From this, a sensitivity of 0.464°/nm is obtained. The small nonlinearity observed (∼3.5%) was attributed to the hysteretic behavior of the PZT translation stage. Fig. 4 illustrates the system response for a step variation of the cavity length of ∼4 nm. The associated phase change is ∼1.81° and the rms fluctuation is ∼0.06°. Considering the experimental detection time constant (0.44 s), it turns out a system static displacement resolution of $\sim 90\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$.

An alternative sensing head was used [lower inset in Fig. 1(a)] to measure temperature variations. The change in the interferometric phase as a function of the temperature is shown in Fig. 5. These data result in a sensitivity of 9.78°/°C and a static temperature resolution of $\sim 0.05^{\circ}\mathrm{C}/\sqrt{\mathrm{Hz}}$.

IV. Conclusion

In this letter, an investigation was accomplished on the application of FBGs for the interrogation of interferometric low-finesse Fabry–Pérot cavities. The proposed scheme is based on the FBG generation of two quadrature phase-shifted signals using the dual-wavelength technique. The concept was tested using two such cavities, one directed to the measurement of displacement and the other to the measurement of temperature, being achieved resolutions of $90\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$ and $0.05^{\circ}\mathrm{C}/\sqrt{\mathrm{Hz}}$, respectively.

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