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Interrogation of a fibre Fabry–Perot interferometer using a π-shifted Bragg grating

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Abstract
A robust all-fibre interferometric interrogation technique based on the wavelength modulation of a π-shifted fibre Bragg grating is proposed. The concept is demonstrated for strain measurement using a Bragg-grating-based Fabry–Perot interferometer. The strain–phase relationship is shown to be linear with a sensitivity slope of $(2.19 \pm 0.02)^\circ/\mu\varepsilon$. A strain resolution of ≈2.4 $\mu\varepsilon$ is demonstrated.

Keywords: Fabry–Perot interferometer, fibre Bragg grating (FBG), optical fibre sensors, strain measurement

Introduction

There has been a considerable interest in using optical fibre sensors for structural health monitoring in smart structure systems. The feasibility to embed optical fibre sensors into the materials allows real-time evaluation of multiple parameters such as load, strain, temperature and vibration. Optical fibre sensors offer important advantages such as electrically passive operation, high sensitivity, multiplexing capabilities and low weight. Among many different types of fibre optic interferometric techniques developed for this purpose, one of the most frequently used is the fibre optic Fabry–Perot interferometer (FFPI) [1].

The first use of the fibre Fabry–Perot structure as a sensor was proposed by Kist and Sohler [2]; thereafter, extensive studies have continued on the intrinsic and extrinsic type of optical fibre sensors, whose interference media are the optical fibre and air, respectively. In one configuration, the extrinsic fibre Fabry–Perot interferometer is an air-spaced Fabry–Perot cavity formed by fixing two separated lengths of the optical fibre into a suitable tube. The alignment is achieved with the capillary tube where the diameter is slightly greater than the cladding diameter of the optical fibre. This structure is of simple implementation and has several applications [3–6]. Many configurations of intrinsic fibre Fabry–Perot interferometers have been proposed in recent years. One technique to fabricate intrinsic FFPI involves sputtering dielectric thin films on the cleaved ends of the fibre spacer and then fusing the cavity in-line with the lead fibres [7]. Another approach uses a short segment of a silica hollow-core fibre spliced between two sections of a single mode fibre to form a mechanically robust in-line optical cavity [8]. After the outcome of fibre Bragg gratings a natural approach to build up intrinsic FFPI structures is using the reflection properties of the gratings, i.e., the FFPI mirrors are two fibre Bragg gratings with identical reflection properties, preferably with large spectral bandwidth [9]. Cavities of this type are much easier to fabricate than other intrinsic FFPI structures and show a considerably higher mechanical strength than the extrinsic FFPI structures.

The fibre Fabry–Perot sensor has shown high potential for the measurement of several parameters. It is one of the preferred interferometric sensor configurations since it is simple to deploy and permits the use of a single fibre, since light is transmitted to the sensor and back through the same fibre; additionally, it has high sensitivity and enables multiplexing operation. Due to this, several layouts based on FFPI sensors have been proposed to measure strain [10–13]. Other authors have demonstrated a multiplexing sensing structure based on a FFPI intereferometer and a fibre Bragg grating sensor for simultaneous measurement of strain and temperature [14]. Using the same analytical tools, a non-contact fibre optic vibration sensor using a Fabry–Perot interferometer was also reported [15].

The recovery of the interferometric phase, which contains the information about a particular measurand that acts on the optical path difference of the interferometer, is not straightforward. One common technique proposed to perform the phase-recovery operation relies on the white light concept. In this case, the light returning from a low-finesse Fabry–Perot interferometer and emitted by an optical source with a coherence length larger than the cavity optical path difference is processed by a second interferometer located in a benign environment [16]. In a spectrally similar technique, the spectrum of the light arriving from the interferometer is modulated by the spectral transfer function of a wavelength division multiplexer (WDM). This WDM is controlled by acting on the coupling length of the device [17]. A different approach uses two interferometric signals that change in quadrature [18–23]. In one development, these signals were obtained using two laser diodes of different wavelengths combined with a specific optical path imbalance for the interferometer [18]. The other reported technique is based on time multiplexing of two interferometric signals derived from the same cavity but that change in quadrature [19]. An alternative solution uses two modes of a multimode laser diode separated by 3 nm to obtain quadrature interferometric signals [20]. Other authors have presented a passive demodulation system based on path-matched differential interferometry, where two air-gap low finesse Fabry–Perot interferometers are used with slightly different cavity lengths to produce two quadrature-shifted intensity signals [21]. A processing technique of this type was also achieved by combining a Mach–Zehnder interferometer with a fibre Bragg grating (FBG) in the context of two-dimensional bend sensing [22]. More recently, the application of FBGs for the interrogation of interferometric low-finesse Fabry–Perot cavities was reported, where the technique is based on the generation of two quadrature phase-shifted signals using a FBG-supported dual-wavelength approach [23].

In this work an interrogation technique of low-finesse Fabry–Perot interferometers based on modulation of a π-shifted Bragg grating is proposed to generate two quadrature phase-shifted signals. The concept is demonstrated in the interrogation of a fibre Fabry–Perot interferometer applied to the measurement of strain.

Theory

The π-shifted grating used in transmission will act as a narrow tuneable filter when submitted to strain. The phase addressing of the FFPI is achieved by displacing the π-shifted grating with a modulated translation stage. Two specific strain values $\varepsilon_{1,2}$ are applied to this structure in order to get interferometric signals with a relative phase difference of 90°.

For each value of the measurand applied to the sensing interferometer, two output voltage signals $V_{1,2}$ are obtained, corresponding to the respective values of strain $\varepsilon_{1,2}$ applied to the π-shifted grating. Using simple mathematical analysis, the interferometric phase can be easily recovered, as is shown next.

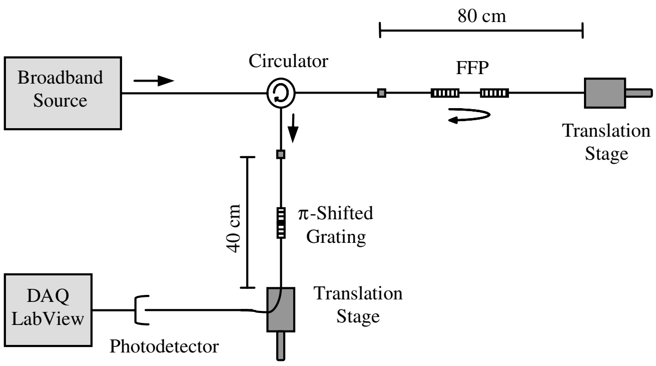

Figure 1. Configuration proposed for interrogation of low-finesse fibre Fabry–Perot interferometers using a modulated π-shifted Bragg grating.

The phase of the low-finesse fibre Fabry–Perot interferometer is given by

$$\phi_j = \frac{4\pi n L_{\mathrm{FP}}}{\lambda_j}, \qquad j = 1, 2 \tag{1}$$

where $\lambda_{1,2}$ are the wavelengths considered, L_{FP} is the cavity length and n is the effective refractive index of the fibre core mode. The relative phase derived from the two selected wavelengths is

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

The phase signals $\phi_{1,2}$ are in quadrature if the separation $\Delta\lambda$ between wavelengths is an odd multiple of $\lambda_2/8nL_{\mathrm{FP}}$, turning $\Delta\phi$ to odd multiples of $\pi/2$. For a specific cavity length it is always possible to define two wavelengths that satisfy this condition. After detection, the interferometric signals related to these two wavelengths are converted into the output voltages, V_1 and V_2, given by the following expressions:

$$\begin{aligned} V_1 &= V_{1o}(1 + k_1 \cos\phi_1) \\ V_2 &= V_{2o}\,[1 + k_2 \cos(\phi_2 + \Delta\phi)] = V_{2o}(1 + k_2 \sin\phi_1) \end{aligned} \tag{3}$$

where V_{1o} and V_{2o} are constant voltage values associated with the system operating conditions and $k_{1,2}$ are the fringe visibilities for each wavelength. Setting $k_1 V_{1o} = k_2 V_{2o}$, the interferometric phase can be demodulated as follows:

$$\phi = \tan^{-1}\left(\frac{V_2 - V_{2o}}{V_1 - V_{1o}} \right) \tag{4}$$

where the ambiguity of π is easily resolved with the use of simple processing algorithms [24–26].

Experimental results

Figure 1 shows the configuration implemented to test the proposed interrogation technique, where a local strain-modulated π-shifted Bragg grating is used to process the phase of a remote sensing interferometer. An erbium-doped broadband source with a bandwidth of 100 nm, a central wavelength of 1550 nm and 100 mW of optical power was used

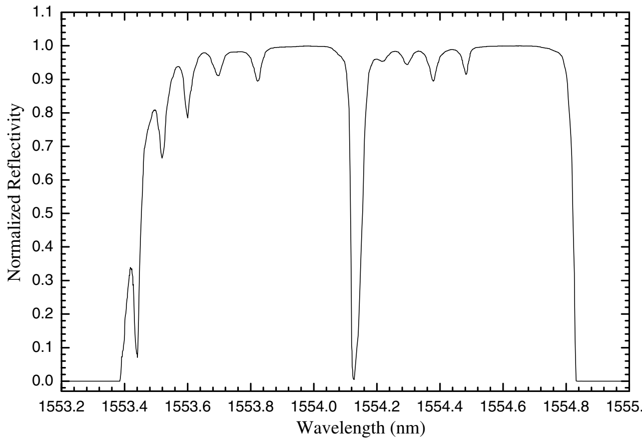

Figure 2. Optical spectrum of the π-shifted Bragg grating.

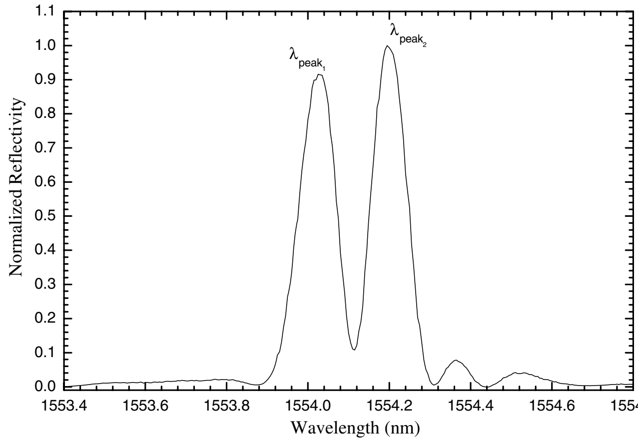

Figure 3. Optical spectrum of the FFPI interferometer based on fibre Bragg grating mirrors.

to illuminate the sensing head through an optical circulator with an insertion loss of 0.1 dB. A standard optical fibre (SM28) was used in all the sensing system. The output filtered signal (some μW) is directed to the photodetector and amplification stage (gain: 1 V μW^{-1}; minimum detectable optical power: 10 pW$\sqrt{\text{Hz}}^{-1}$), converted into a digital signal by a DAQ board and acquired by LabView™. Strain was applied to both FFPI and the π-shifted grating by means of a micrometric translation stage. The system was also placed in a controlled environment in order to stabilize the temperature.

The π-shifted Bragg grating utilized in this experiment has the optical spectrum shown in figure 2. It was fabricated in-house using a phase-mask-based technique. The FWHM of the central notch is ≈40 pm and the bandwidth of the rejection band is 1440 pm. The central notch acts as a tuneable wavelength filter that, when scanned over the interferometer channelled spectrum, will change the output in a way that is equivalent to a certain interferometric phase change. The temperature sensitivity of this grating is the same as that of a uniform Bragg grating.

To perform the experiment, a fibre-Bragg-grating-based FFPI was fabricated with a fringe periodicity larger than that of the central notch of the demodulation π-shifted grating. This optical fibre structure was obtained directly during the grating writing process by placing a capillary tube at the middle of the phase mask. This process forms two shorter twin gratings with a small fibre length between them. The respective optical spectrum is presented in figure 3.

The fringe periodicity is ≈170 pm. The FWHM of the fringes and of the envelope are ≈90 pm and ≈425 pm, respectively. The reflection spectrum of the interferometer is the product of two components. The first component is the reflection spectrum of the gratings, which forms an envelope function. The second component is a cosinusoidal modulation due to the interference between the waves reflected from the gratings. Both components in the spectrum change due to the influence of the measurand. The relative shift of the Bragg wavelength, which determines the centre position of the envelope function in the spectrum, is the same as in traditional Bragg grating sensors. If the measurand has an equal effect on the twin gratings and in the fibre between them, the cosinusoidal modulation component shifts at the same rate as the envelope. Therefore, under the measurand influence, the reflection spectrum of the interferometer shifts while maintaining its shape, i.e., there is a phase change. In particular, this phenomenon occurs when the measurand is strain. However, considering that the two selected wavelengths for phase processing are fixed, it is desirable for accurate reading that the envelope modulation of the interferometric fringes due to the gratings' spectral displacement not be significant in the measurement range.

For the phase processing concept to work properly, it is necessary that the transmission rejection band of the π-grating be larger that the spectral widths of the gratings in the FFPI; also the reflectivity of this grating must be as high as possible. In the present case, these conditions are approximately fulfilled, as turns out from the comparison of figures 2 and 3.

The step cycle between the two processing wavelengths is performed by strain modulating the π-shifted grating. The notch is cantered at the peak wavelength of the envelope spectrum of the FFPI that corresponds to the strain value ε_1. To tune the notch from the wavelength λ_{peak1} to the wavelength λ_{peak2} in figure 3 (170 pm; $\Delta\phi = 2\pi$), it was necessary to apply a strain step of 42.5 $\mu\varepsilon$ to the π-shifted grating; therefore, when $\varepsilon_2 = (\varepsilon_1 + 10.6)\mu\varepsilon$, an output signal corresponding to an interferometric phase change of 90° is obtained. For each strain value applied to the sensing interferometer, the two signals $V_{1,2}$ are obtained and processed as indicated before to get the measurand information. In this experiment the switching frequency between the two-quadrature interferometric positions was ≈1 Hz. The results are shown in figure 4.

The phase dependence with strain is linear, with a slope (sensitivity) of $(2.19 \pm 0.02)^\circ/\mu\varepsilon$. The evidence of this linear relation is also a confirmation of a well-adjusted quadrature demodulation operation. It has been quantified before in the context of interferometric phase recovery, using quadrature signals, that a deviation from this condition, both in phase (phase shift different to $\pi/2$) and in amplitude (quadrature components with different amplitude), introduces

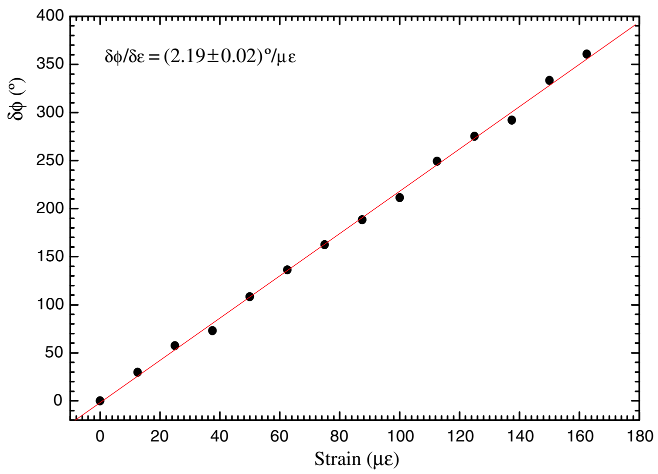

Figure 4. Phase change of the fibre Fabry–Perot interferometer versus applied strain.

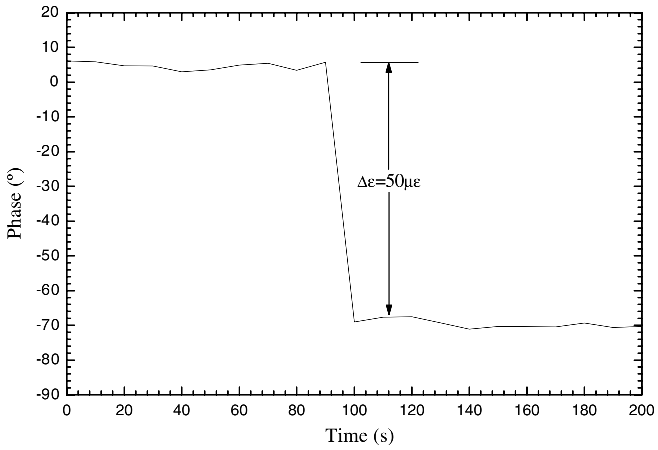

Figure 5. Strain resolution of the sensing system.

significant nonlinearity in otherwise linear behaviour between the interferometric phase change and measurand variation [27].

To determine the strain resolution achievable with this system, a strain step variation of 50 $\mu\varepsilon$ was applied to the FFPI and the corresponding output variation registered, as shown in figure 5. From the observed phase step and phase fluctuations a strain resolution of ≈2.4 $\mu\varepsilon$ is obtained. In what concerns the measurement range, with the configuration proposed in this work, there is a first constraint which is the need of the envelope of the FBG mirrors to not move out from the position where it is located relative to the notch of the π-shifted grating; a second constraint lies in the fact that the spectral function of these FBG mirrors must be located within the reflection bandwidth of the π-shifted grating. The combination of these two issues points out the need for FBG mirrors with a large spectral bandwidth which, however, must be smaller than the π-shifted grating reflection band. In the experiment performed, the last condition is well fulfilled in view of the reflection spectral bandwidths of the FBG mirrors and π-shifted grating (≈0.4 nm and ≈1.4 nm, respectively). Considering the first constraint, the spectral width of the FBG mirrors, a Bragg wavelength displacement for these gratings of ≈0.2 nm is probably acceptable, which for the case of strain measurement translates into a measurement range of ≈170 microstrain, which is approximately the range considered in figure 4. However, it must be emphasized that substantially larger measurement ranges can be achieved by increasing the Fabry–Perot gratings' spectral bandwidth, not compromising the second constraint mentioned above. Also here, it is possible to fabricate π-shifted gratings with a spectral reflectivity function several nanometers wide. Therefore, balancing all these issues, it is reasonable to assume a strain measurement range around 1 millistrain feasible with this system.

When dealing with the measurement of dynamic parameters, one limitation of this technique is the speed of the scanning between the two positions corresponding to interferometric quadrature signals, which limit its applicability to signals with slow dynamics. However, it must be emphasized that the mechanical tuning does not have large amplitude, considering the phase step that is needed ($\pi/2$). Due to this characteristic, the system worked through several weeks without evidence of mechanical creep phenomenon.

The interrogation technique proposed here can be applied to the interrogation of any type of two-beam interferometer and not only to low-finesse FFPI interferometers. It can also be used in the implementation of other interferometric interrogation techniques based on wavelength modulation at a reduced cost when compared with the standard approach based on the modulation of a tuneable laser. Furthermore, the recovered information is not limited to the case of static or quasi-static parameters, dynamic measurand readout being also feasible. In view of the limited amplitude of the strain modulation that needs to be applied to the π-shifted Bragg grating (to obtain the two quadrature-related interferometric signals), and also the fact that the fibre spring constant can be decreased by reducing the fibre diameter (for example, through an etching process), it is foreseen that this interferometric interrogation technique can be used in situations where the measurand changes in time with frequencies up to 100 Hz. Therefore, it is acceptable to state that this technique is a viable and economic alternative to the interrogation of interferometric sensing systems in a substantial range of applications.

Conclusions

In this work an interrogation technique for low-finesse Fabry–Perot interferometers based on quadrature modulation of a π-shifted Bragg grating was reported. The concept was demonstrated for the measurement of strain applied to a fibre-Bragg-grating-based Fabry–Perot interferometer. A sensitivity of $(2.19 \pm 0.02)^\circ/\mu\varepsilon$ was obtained and a strain resolution of ≈2.4 $\mu\varepsilon$ achieved.

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