Optics Communications 285 (2012) 2826–2831

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Resolution and sensitivity enhancements in strong grating based fiber Fabry–Perot interferometric sensor system utilizing multiple reflection beams

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ARTICLE INFO

Article history:
Received 11 September 2011
Received in revised form 13 February 2012
Accepted 14 February 2012
Available online 26 February 2012

Keywords:
Fiber Bragg grating
Fiber Fabry–Perot interferometer
Sensitivity enhancement
Multiple reflection beams

ABSTRACT

We investigate an asymmetric intensive fiber Bragg grating (FBG) defined Fabry–Perot (F–P) sensor system decoded by a multiple-path-matched Michelson interferometer. The interrogation of higher order reflection beams cannot only solve the problem of the degraded resolution induced by the spectral mismatch of the FBGs, but also amplify the effect of the fiber strain on the phase of the light. We demonstrate multiple reflection beams in the F–P cavity based on the concept of the FBG effective length for constructing respective interrogation interferometers, and present a cost function with optimized system parameters to improve noise properties. The performances of interrogating the second, third and fourth order reflection beams are compared in a strain sensing experiment arrangement. Under the condition of the same optical path length mismatch, the interrogation of the fourth order reflection beam can achieve 9.8 dB sensitivity enhancement and 3 dB resolution promotion compared with the result using the second order reflection beam.

1. Introduction

Fiber Fabry–Perot (FFP) interferometers have been researched for their number of practical sensing applications due to their outstanding features such as miniature size, easy manufacture, high sensitivity, low cost and minimum cross sensitivity [1,2]. Conventional FFP sensors classified as extrinsic, hybrid and intrinsic types are formed by joining different kinds of light propagation media together to utilize fiber end reflection, e. g. fiber and air [3], single-mode fiber with hollow-core fiber [4], and coated fiber joint spliced by fusion [5]. Fiber Bragg gratings (FBGs) as intrinsically channeled in-fiber partial reflectors provide a new prospect for the development of FFP sensors [6]. A Fabry–Perot (F–P) cavity is constructed with two FBG serving as mirrors [7]. This twin grating configuration heritages FBG's good multiplexing ability, promotes a robust mechanical strength and offers an ultra high sensitivity with a long cavity compared with traditional types [8]. Interferometrically interrogated FBG defined F–P interferometers have demonstrated a resolution of 3.82 $p\varepsilon/Hz^{1/2}$ theoretically [9] and 72.2 $p\varepsilon/Hz^{1/2}$ experimentally [10] using a 30 cm-long cavity. And the degraded resolution was analyzed based on the effect of the path length mismatch between the cavity length and the path length difference of the interrogation interferometer. In fact, the mismatch of FBGs in spectral profile also has a big influence upon the performance of the constructed FFP sensor system through its effect on the fringe visibility [11]. The spectral mismatch can be induced by imperfect fabrications [12,13] and environmental disturbances [14]. To the best of our knowledge, there is no valid solution to this problem besides better shielding FBGs and desensitization with certain kinds of polymer [15].

The detection resolution of a FBG based interferometric sensor system depends on the time delay difference between interference beams [9]. In a tandem interferometer arrangement, the FBG defined F–P system can achieve ultra-high sensitivity by using a long cavity apart from a weakening resolution. However, in a practical system, the size of the optical sensors is chosen by the application-dependent tradeoffs between sensitivity, dynamic range and dimensional parameters [16]. Packaging technologies have been investigated to improve the responsivity of the bare fiber. Specialized coatings for the sensing fiber and wrapping the fiber on compliant mounting structures have been generally identified as promising approaches [17]. Besides packaging techniques, laser phase noise suppression [18] and optical sensing configuration improvement [16] have also been demonstrated. Nested multiple interferometers based on distributed Bragg reflectors have been demonstrated to provide flexibility in designing interferometric sensors for applications of adaptive arrays, where different lengths of sensing coils are addressed via respective interrogation wavelengths [19]. All these techniques above are based on sensing element design with increasing complexity in manufacture and increments of cost and dimensions.

In this paper, we investigate the interrogation of multiple reflection beams in a FBG constructed F–P sensor system to achieve resolution and sensitivity enhancements at the same time. The sensing scheme provides a valid solution to the spectral mismatch problem and an additional means of responsivity improvement combined with

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0030-4018/$ – see front matter
doi:10.1016/j.optcom.2012.02.024

conventional packaging techniques. Section 2 describes the multiple reflection beams in a strong grating based asymmetric F–P cavity for interferometric interrogation. In Section 3, system parameters are optimized to improve the detection resolution using a cost function. In Section 3.2, the interrogation of different order reflection beams is evaluated experimentally. Section 4 draws the conclusion.

2. Theory

Many investigation schemes have been proposed based on symmetric week FBG defined F–P interferometers. The reflection spectrum of this kind of FFP cavities is often described as a two-beam interference, due to the fact that the power of the reflected light attenuates hundred times smaller after each round trip in the cavity [20]. And the performance of the sensor system depends on the actually asymmetric spectral profiles of FBGs [11]. We investigated a strong grating based asymmetric F–P sensor system instead of nominally symmetric configurations. Multiple reflection beams generated between the two intensive Bragg mirrors can amplify the effect of fiber strain on the phase of the light. Identical spectral components are also formed and utilized in this high finesse cavity.

2.1. Interrogation of multiple reflection beams

Interferometrically interrogated sensor systems always employ path length compensating interferometers. In order to decode multiple reflection beams with better noise properties, the effective cavity of the constructed asymmetric F–P interferometer needs to be analyzed carefully. The effective length of a FBG is determined by the group delay of the grating, which increases with the grating physical length and decreases with the diffraction efficiency. And the grating effective length at its Bragg wavelength is expressed as [21]

$$L_{eff} = L\frac{\sqrt{R}}{2\operatorname{atanh}\left(\sqrt{R}\right)}, \tag{1}$$

where L and R represent the physical length and the reflectivity of the FBG, respectively. The effective length of a strong FBG characterizes nonlinearity with respect to the reflectivity, and the equivalent position of reflection approaches to the incidence end with a bigger R.

The multiple reflection beams in a strong grating based asymmetric F–P cavity is illustrated in Fig. 1. L_{eff1} and L_{eff2} are respective effective lengths of the two FBGs. P_0 is the incidence light power. And a_1, a_2, a_3 and a_4 are reflection amplitudes which describe propagation paths of the first, second, third and fourth order reflection beams, respectively. They can be written as

$$a_1 = r_1, a_2 = t_1 t_1' r_2 \exp(2j\beta L_0), a_3 = t_1 t_1' r_2 r_1' r_2 \exp(4j\beta L_0), \\ a_4 = t_1 t_1' r_2 \left(r_1' r_2\right)^2 \exp(6j\beta L_0). \tag{2}$$

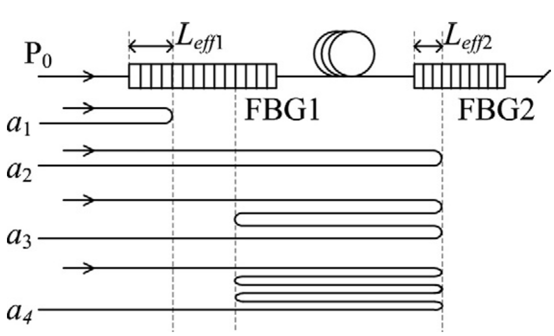

Fig. 1. Multiple reflection beams in an asymmetric FFP cavity.

Considering the different spectral profiles of the two FBGs, multiple reflection beams exhibit identical spectral components under the band filtering effect in the cavity besides intensity attenuation. And this will be further discussed in the Experiment section. Referring to Fig. 1, the effective cavity length for different order reflection beams can be figured out. Three Michelson interferometers are constructed to decode the interferometric signals between a_2 and a_1, a_3 and a_1, and a_4 and a_1, respectively. Therefore, the path length differences of respective interrogation interferometers can be expressed as follows:

$$h_1 = L_0 + L_1 - L_{eff1} + L_{eff2}, h_2 = 2h_1 - 2\left(L_1 - 2L_{eff1}\right), \\ h_3 = 3h_1 - 4\left(L_1 - 2L_{eff1}\right), \tag{3}$$

where L_0 and L_1 denote the distance between the two gratings and the physical length of FBG1, separately. It is clear that the path length differences of the three interferometers are not in the relationship of multiple lengths because of the asymmetric configuration of the F–P cavity, which cannot be neglected in the white light interferometry.

2.2. Optimization of system parameters

The detection resolution of a sensor system is determined by the noise equivalent signal, and the signal-to-noise ratio (SNR) is expressed as the fringe visibility of interferometric signals. The key to satisfying application requirements in this scheme is to promote the SNR of the interferometric signals between two beams with enormous intensity differences. Therefore, parameters of FBGs and couplers in the interrogation interferometers are optimized to balance the intensities of the two interference beams.

An interferometric FFP sensor system with multiple reflection beam interrogation is shown in Fig. 2. The second, third and fourth order reflection beams are decoded by three Michelson interferometers (MIs) and respective interferometric signals are collected by corresponding photoelectric detectors (PDs). Denoting the two output ports in a MI as port1 and port2, there are three output modes which are light in-out through port1 (port preserving case), light in-out through port2, and light in through port1 and out through port2 (port flipping case). And they can be written as PP1, PP2 and PF for short, respectively. The MIs shown in Fig. 2 are in the PF output mode.

The optimization of system parameters is achieved by weakening the intensities of the multiple reflection beams as less as possible, which is implemented through letting the beams travel along the short arm of the MI which has a high coupling ratio with the input port fiber. In the MI with an optimized coupler according to port1, PP1, PF and PP2 describe respective output modes with balancing, preserving and enlarging the intensity differences of the two interferometric beams. Denote k_1 and $k_2 = 1 - k_1$ as the coupling

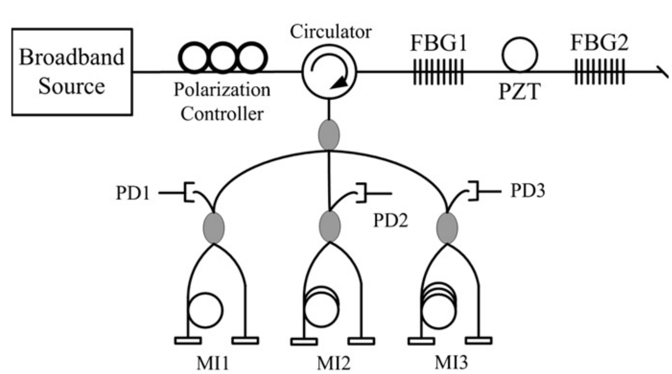

Fig. 2. Interferometric FFP sensor system interrogated by multiple-path-matched Michelson interferometers.