

Micrometric displacement sensor based on the strain of a fiber Bragg grating with heterodyne detection of intensity in a Mach-Zehnder interferometer.

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Abstract. This paper describes the implementation and characterization of a displacement sensor according to the strain of a fiber Bragg grating. The system is able to obtain measurements on micrometer scales through heterodyne detection of intensity in a Mach-Zehnder interferometry in fiber optic. For the displacement characterization, the fiber Bragg grating was attached from one end meanwhile at the other end a tension was induced by a high-precision rotation mount. Experimental results are presented for which varying the angular displacement we obtain a linear response in the amplitude of the intensity, determining a sensitivity of 0.77 pW/ μm with a displacement size of 48.80 μm in a dynamic range from 0 μm to 488 μm .

1. Introduction

The fiber optic, besides the data transmission through long distances, is able to provide additional information about the environment where it is located. This characteristic is possible by measurements in the properties of the confined light as intensity, wavelength, phase and polarization [1]. Most fiber optic sensors based their operation on interferometric principles, being the Mach-Zehnder interferometer the setting most used owing to they have extremely flexible geometries and high sensitivities that allow the possibility of sensing a wide variety of parameters [2, 3]. The Mach-Zehnder interferometer is an optical instrument capable of high-resolution phase analysis [4]. The basic elements of a fiber optic Mach-Zehnder interferometer consist in a spectral light source to feed the device, a fiber beam splitter to produce two different optical paths; the sensing and reference path. A transducer element is placed on each interferometer arm where one will be under the environmental



effects whereas the other arm will be isolated to be used as a reference. Finally homodyne or heterodyne demodulator is used to estimate the change in optical paths which is a function of the physical variable to be measured [5]. The transducer most used to detect strain is the fiber Bragg grating (FBG) and based on this parameter the displacement is indirectly measured. The FBG is a periodic variation of the refractive index into the core of an optical fiber. This periodic structure will reflect a specific optical wavelength dependent on the periodicity. To characterize the FBG as displacement sensor, as a strain is applied to the FBG periodicity change, vary the periodicity vary the reflected wavelength known as Bragg wavelength [6]. The strain applied to the FBG is expressed in microstrains ($\mu\epsilon$) which is a dimensionless unit that roughly describes the elongation of 1 μm in an optical fiber with a length of 1 m [5].

The electromagnetic waves at the output of the interferometer are detected with a photodetector and the generated photocurrent is given by the square of the total electric field, this is described by Equation 1.

$$I(t) = |A_R \cos(\omega_R t + \phi_R) + A_S \cos(\omega_S t + \phi_S)|^2 \quad (1)$$

Where the subscripts R and S indicate that each parameter describes the reference and sensing wave respectively. A is the amplitude of each wave, ω is the angular frequency, while ϕ is the relative phase for the reference and sensing wave. When a strain is applied each interferometer arm experiences an increase in relative phase, which is expressed in Equation 2.

$$\phi = \frac{2\pi n_{eff} L}{\lambda_B} \quad (2)$$

The relative phase of an optical beam depends on the optical pathlength [1]. n_{eff} is the effective refractive index of the optical fiber, L indicates the length of the optical path and λ_B is the Bragg wavelength of the FBG. We dropped the losses effect by fiber couplers. Therefore, the interferometric output signal in steady state is given by

$$I(\phi) = A \cos(\Delta\phi) \quad (3)$$

Where

$$\Delta\phi = \phi_R - \phi_S \quad (4)$$

The amplitude A depends on A_R , A_S and the responsivity of the photodetector [7]. As a strain is applied the phase shifts change and this is clearly observable in the intensity detected. Substituting Equation 2 in Equation 4 and the resulting of it in Equation 3, we obtain

$$I(\phi) = A \left[\cos \left(\frac{2\pi n_{eff} (\lambda_{BS} L_R - \lambda_{BR} L_S)}{\lambda_{BR} \lambda_{BS}} \right) \right] \quad (5)$$

Where λ_{BR} and λ_{BS} are the Bragg wavelength in nm of the reference FBG and the sensing FBG, respectively. Meanwhile L_R and L_S are the pathlength of each interferometer arm.

2. Materials and methods

A FBG of OEMARK brand was used in each arm of the Mach-Zehnder interferometer. By means of an interrogation system O/E Land OEFSS-200a we characterize each FBG to know their properties. The reference FBG has a Bragg wavelength of 1549.50 nm and the Bragg wavelength of the sensing FBG was 1550.08 nm. A strain was applied in the sensing FBG in order to appreciate the Bragg wavelength shift. The fiber optic interferometer, as shown in Figure 1, was built with a single mode fiber SMF-28 and a super-luminescent diode (SLD) was used as a source. The SLD has a spectral range from 1535 nm to 1565 nm and a central wavelength of 1547 nm. The optical power used was of 8 mW. To compose the interferometers arms we used a fiber splitter (C1), later the sensing FBG was coupled. In a second splitter (C2) the reference FBG was coupled. The reflected wavelength in each FBG contains a part of the spectrum and it was combined by a 2x1 coupler (C3). The intensity at the exit of the coupler C3 was measured by a Thorlabs S155C photodetector (PD). Through a Thorlabs PM100USB interface we send the reading data to PC where by an application developed by Thorlabs in LabVIEW, and improved for us, the signal conditioning and processing of information in a database is achieved.

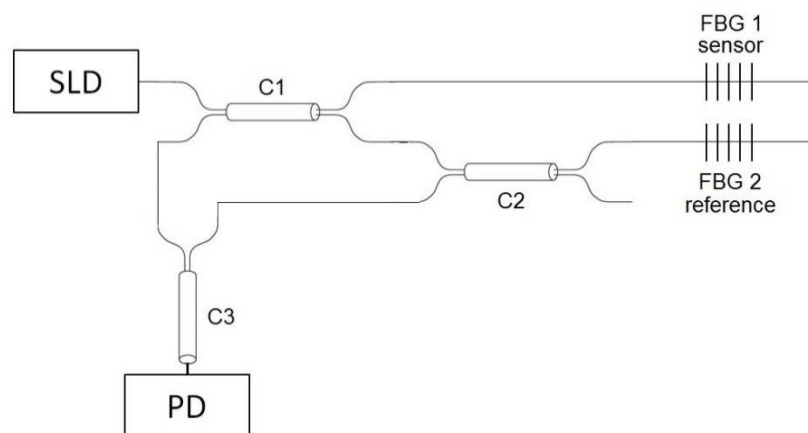


Figure 1. Experimental setup.

To displacement characterization based on the FBG strain, we attached with scotch tape the ends of a FBG section with a length of 27 cm. One end was fixed on an optical post assembly meanwhile the other end was attached on a high-precision rotation mount in order to strain the FBG section. The minimum angular displacement unit of the high-precision rotation mount was equivalent to a strain of $90.37 \mu\epsilon$ and in turn this was equivalent to a linear displacement of $24.40 \mu\text{m}$.

3. Experimental results

The reflectivity spectral of the sensing and reference FBG were obtained by means of an interrogation scheme. Figure 2 shows the reflectivity spectral of each FBG.

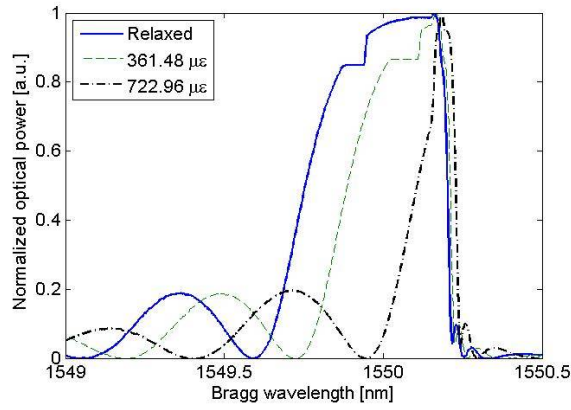


Figure 2. Reflectivity spectral of the sensor FBG and reference FBG.

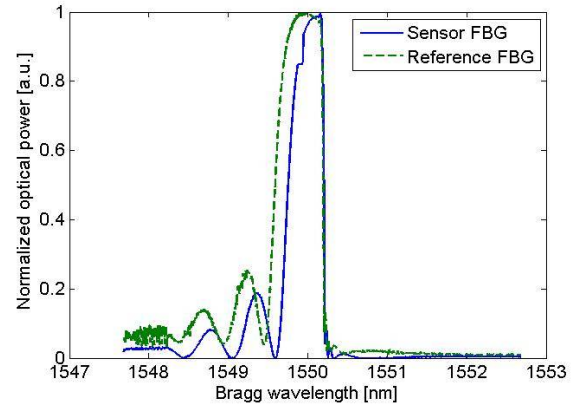


Figure 3. Displacement of Bragg wavelength in function of the strain applied in the sensor FBG.

The reflectivity spectrum was normalized owing to splices in the optical fiber the optical power amplitude varies in each FBG. The displacement of Bragg wavelength is measurable in function of the applied strain. In Figure 3 we appreciate the reflectivity spectral and the Bragg wavelength when the FBG is relaxed but whenever a measurable strain is applied the reflectivity spectral is reduced and a shift occurs in the Bragg wavelength.

To know the relation between the applied strain and the shift Bragg wavelength we realized a series of measurements with the sensor FBG. In a strain range from 0 $\mu\epsilon$ to 903.70 $\mu\epsilon$ with a strain size of 90.37 $\mu\epsilon$, shown in Figure 4, an almost linear behaviour was obtained that fits in Equation 6.

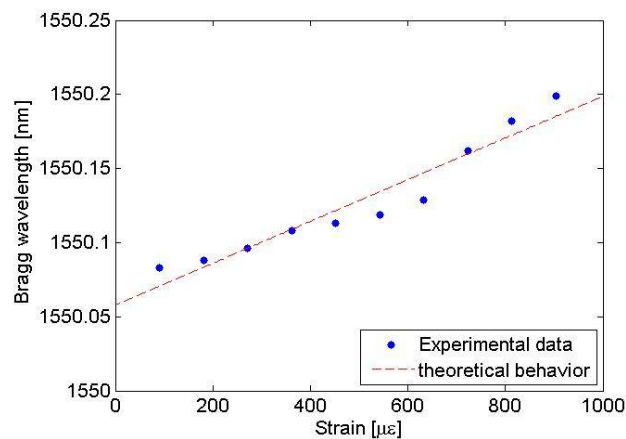


Figure 4. Bragg wavelength in function of applied strain.

$$\lambda_B(\mu\epsilon) = 0.00014 \left[\frac{\text{nm}}{\mu\epsilon} \right] x[\mu\epsilon] + 1550.06 [\text{nm}] \quad (6)$$

Knowing the relation between strain and shift wavelength we demonstrated that the minimum appreciable displacement was a strain of $180.74 \mu\epsilon$ equivalent to a lineal displacement of $48.80 \mu\text{m}$. We realize the characterization of the sensor through a series of measurements, as shown in Figure 5, which consisted in step size of $180.74 \mu\epsilon$ for a total of 10 steps and returning to the relax state of the sensing FBG. For a linear fitting we did an average of every intensity data step in order to obtain a mathematical expression of the sensor behaviour.

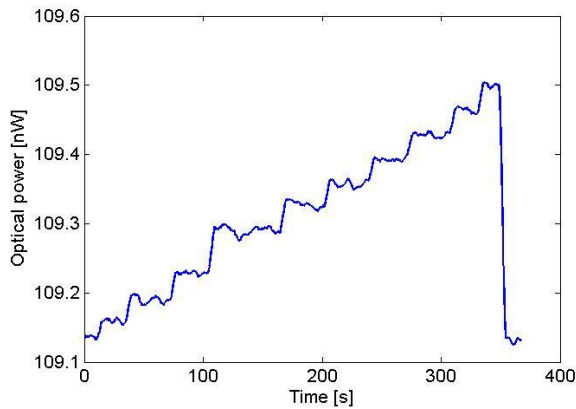


Figure 5. Measurement series from $180.74 \mu\epsilon$ to $1807.40 \mu\epsilon$.

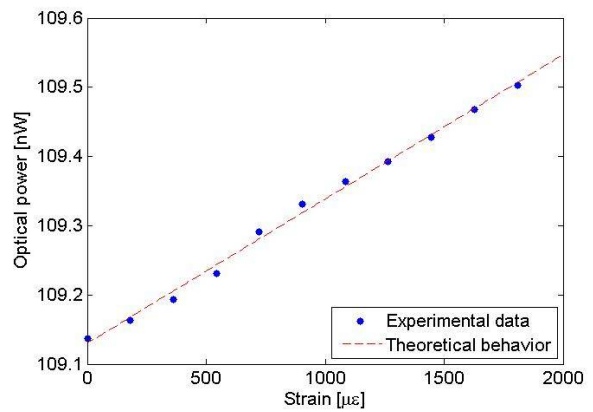


Figure 6. Linear fitting of the displacement sensor based on strain.

With a dynamic range from $0 \mu\epsilon$ to $1807.40 \mu\epsilon$ and strain size of $180.74 \mu\epsilon$, we obtain another linear behaviour described by Equation 7.

$$I(\mu\epsilon) = 0.00021 \left[\frac{\text{nW}}{\mu\epsilon} \right] x[\mu\epsilon] + 109.13 [\text{nW}] \quad (7)$$

An interpretation of Equation 7 is that for a strain in the sensing FBG of $1 \mu\epsilon$ we obtain a change in the intensity of 0.21 pW at the exit of the Mach-Zehnder interferometer. This change was imperceptible but to appreciate a considerable change, as shown in Figure 5, we applied a strain of $180.74 \mu\epsilon$ and in turn this was equivalent to an intensity change of 37.95 pW . For a description of the intensity in function of the lineal displacement, we obtained a characteristic expression described by Equation 8.

$$I(\mu\text{m}) = 0.00077 \left[\frac{\text{nW}}{\mu\text{m}} \right] x[\mu\text{m}] + 109.13 [\text{nW}] \quad (8)$$

In the same way a linear behaviour was appreciated with a sensibility of $0.77 \text{ pW}/\mu\text{m}$, where the minimum lineal displacement was $48.80 \mu\text{m}$ in a dynamic range from $0 \mu\text{m}$ to $488 \mu\text{m}$.

4. Conclusions

The interferometric sensor for strain described bellows provides a simple method that allows us the possibility to measure other parameters in the same system. Experimental results show that this technique has an acceptable sensibility. Mathematically we obtained a sensibility of almost 0.21

pW/ $\mu\epsilon$ but the resolution that the system detect is as 180 times the obtained sensibility. In a displacement characterization we obtain an indirect sensibility 0.77 pW/ μm . The system resolution depends on the photodetector responsivity but if we want improve our resolution we need to considerate all the variables that are introducing noise in the system. Furthermore the fiber optic interferometric system has a lot of fiber splices and couplers who generate losses that affects its performance.

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References

- [1] Bellil H and Abushagur M 2000 *Heterodyne detection for Fiber Bragg Grating sensors, Optics & Laser Technology* **32** 5 pp. 297–300 .
- [2] Ghatak A and Thyagarajan K 2000 *Introduction To Fiber Optics* 2nd edition Cambridge University Press
- [3] Maity A B 2013 *Optoelectronics and Fiber Optics Sensors*, PHI Learning
- [4] Jackson D A Dandridge A and Sheem S K Measurement of small phase shifts using a single-mode optical-fiber interferometer 1980 Opt Lett **5**(4) pp. 139–141
- [5] Yin S, Ruffin P B and Yu F T S 2008 *Fiber Optic Sensors* 2nd edition CRC Press
- [6] Cusano A, Cutolo A and Albert J 2011 *Fiber Bragg Grating Sensors: Recent Advancements, Industrial Applications And Market Exploitation* Bentham Books
- [7] Wu Q et. Al 2010 *High resolution temperature insensitive interrogation technique for FBG sensors, Optics & Laser Technology* **42** pp. 653–656 (2009).