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Research of a double fiber Bragg gratings vibration sensor with temperature and cross axis insensitive

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ABSTRACT

A novel double fiber Bragg gratings (FBGs) vibration sensor with temperature and cross axis insensitive is developed. In order to eliminate the influences of the temperature drift, the symmetrical pull–push structure is adopted. The sensor head is based on two elastic material cylinders, into which two matching FBGs are embedded respectively, loaded with a seismic mass. Closed-form analytical formulas describing the resonant frequency and sensitivity of the FBG vibration sensor are provided which may be utilized to tailor the sensor performance to specific applications. The phase generation carrier (PGC) interrogation technique based on the unbalanced Michelson interferometer is studied. Experimental results of a prototype vibration sensor show that the acceleration sensitivity of the FBG vibration sensor reaches 450 pm/g in the frequency range of 5–100 Hz. The resonant frequency of the FBG vibration sensor is 210 Hz. For a temperature change from 0 °C to 50 °C, the wavelength shift of the sensor is almost 0 without any temperature compensation schemes. The noise floor of the FBG vibration sensor is obviously improved and reaches −100 dB/Hz$^{1/2}$ over the range of 40–100 Hz. The experimental results prove the good performance of the FBG vibration sensor.

1. Introduction

The first fiber Bragg grating (FBG) was reported approximately three decades ago [1,2], and since then there has been considerable interest devoted in the applications of FBG based sensors. The success of FBG-based sensors on the measurement of strain has facilitated the modification of sensor designs that can deal with other measurands such as vibration. And over the last 10 years, FBG vibration sensor has become a hot research topic and begun to be extensively developed in a range of applications, such as in early warning of earthquake and tsunami [3], structural health monitoring [4], oil detection [5] and so on. Several designs of the FBG vibration sensor have been suggested to detect the acceleration signal, such as those based on breadthwise embedded structure [6], beam-plates based structure [7], and cantilever beam based structure [4,8,9]. All of these methods are easy to implement, and has been used extensively. However, in order to eliminate the influences of the temperature drift and cross axis talk, additional temperature and cross axis talk compensation schemes must be adopted for the proposed structures. And these mentioned structures cannot be easily extended to achieve three-dimensional acceleration sensing.

In this paper, we report a novel FBG vibration sensor with temperature and cross axis insensitive. This FBG vibration sensor is based on two matching FBG lengthways embedded into a commercially available elastomer with symmetrical pull–push structure. This design can be easily extended to achieve multi-axis acceleration sensing. The excellent performances of this FBG vibration sensor are demonstrated by its experimental results.

2. Sensor design and theoretical analysis

2.1. The FBG sensing principle

FBGs are obtained by producing a periodic variation in the index of refraction along a short section (1–2 cm) inside the core of an optical fiber. The peak reflectivity wavelength, called the Bragg wavelength, λ_B, obeys in good approximation Bragg's law [10]

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where Λ is the grating period and n_{eff} is the effective refractive index of the FBG.

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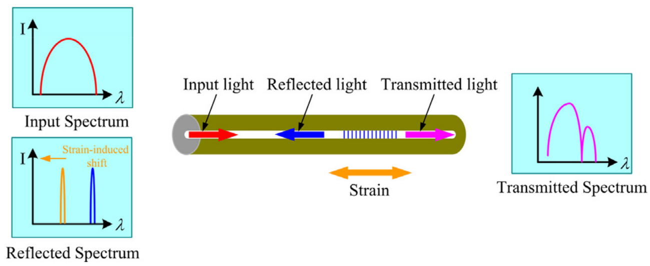

Fig. 1. Schematic of the FBG sensing principle.

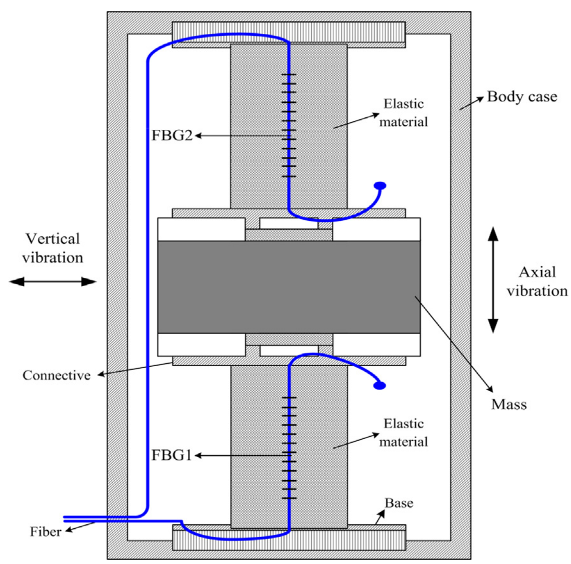

Fig. 2. Schematic of the FBG vibration sensor head.

Fig. 1 shows the sensing principle of the FBG. When the FBG is strained, the relative change in Bragg wavelength is expressed as [11]

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon \tag{2}$$

where p_e is the effective elasto-optic coefficient of the fiber core material and ε is the longitudinal strain on the FBG. Typically, for the silica optical fiber, Eq. (2) can be written as [11]

$$\frac{\Delta\lambda_B}{\lambda_B} = 0.78\varepsilon \tag{3}$$

The Bragg wavelength λ_B is also affected by temperature changes. The relative change in the Bragg wavelength due to temperature change is expressed as [12]

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\Delta T \tag{4}$$

where α is the thermal expansion, ξ is the thermo-optic coefficient and ΔT is the change in temperature experienced at the FBG location. For pure strain or vibration measurements, effects of temperature change on the Bragg wavelength have to be suitably compensated.

2.2. Sensor design

Fig. 2 shows the schematic diagram of the FBG vibration sensor head proposed in this paper. It consists of a mass, two FBGs which are embedded in elastic materials, and package. Principally, the sensor head is based on two elastic material cylinders loaded with a seismic mass. The FBG is lengthways embedded in each of the elastic material cylinders. A constant tension is applied during the embedding process. When the FBG vibration sensor is under axial vibration, one of the cylinders is compressed while the other one is expanded, leading to variations of the lengths of the FBGs embedded in the cylinders. Consequently, the peak reflectivity wavelengths of the FBGs change. When the sensor is under vertical vibration, the two face-to-face cylinders have the same deformation. The same change of the Bragg wavelength of two FBGs is counteracted. Therefore, no signal will be detected in sensor. Hence, the sensor is only sensitive to the axial vibration.

2.3. Theoretical analysis

Generally, the analysis of this FBG vibration sensor is based on a single elastic material cylinder loaded with a seismic mass. Since the above mentioned sensor is performed in a push–pull way, its induced wavelength shift is twice as the wavelength shift induced by a single elastic material cylinder, assuming the same deflection of the seismic mass. However, the overall sensitivity at frequencies well below the resonant frequency of the mass spring assembly does not change as in the two-cylinder version, that is, twice the force is required in order to achieve the same deflection. The only change occurs in the resonant frequency of the vibration sensor assembly, which is larger by a factor of $2^{1/2}$ in the double elastic material cylinder version because of the doubled stiffness.

The Young modulus E of the elastic material cylinder can be expressed by

$$E = \frac{ma/\pi R^2}{\Delta H/H} \tag{5}$$

where R and H are the radius and the length of the elastic material cylinder, respectively, ΔH is the length shift of the elastic material cylinder, m is the mass of seismic mass, a is the unknown ground acceleration. When the sensor is under axial vibration, the longitudinal strain ε applied at the FBG can be expressed as

$$\varepsilon = \frac{\Delta H_1}{H} = \frac{\Delta H_2}{H} = \frac{ma/2}{E\pi R^2} \tag{6}$$

By substituting Eq. (6) into Eq. (2), the relative wavelength shifts of the FBGs can be obtained as follows

$$\frac{|\Delta\lambda_{B1}|}{\lambda_{B1}} = \frac{|\Delta\lambda_{B2}|}{\lambda_{B2}} = 0.78\frac{ma/2}{E\pi R^2} \tag{7}$$

where $\Delta\lambda_{B1}$ and $\Delta\lambda_{B2}$ are the Bragg wavelength shift of FBG1 and FBG2, respectively. For the push–pull structure, the total wavelength shift of the sensor is calculated by

$$\Delta\lambda = |\Delta\lambda_{B1} - \Delta\lambda_{B2}| = 0.78\frac{\lambda_{B1} + \lambda_{B2}}{2}\frac{ma}{E\pi R^2} \tag{8}$$

Hence, the acceleration sensitivity of the sensor, M_a, is given by

$$M_a = \frac{\Delta\lambda}{a} = 0.78\frac{m}{E\pi R^2}\frac{\lambda_{B1} + \lambda_{B2}}{2} \tag{9}$$

The resonant frequency of this mass-spring system, f_0, can be written as [13]

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{2E\pi R^2}{mH}} \tag{10}$$

Considering the contribution of the cylinder mass to the inertia of the system, the acceleration sensitivity and resonant frequency are given as flows [13]

$$M_a = \frac{\Delta\lambda}{a} = 0.78\frac{m + (2/3)m_{cyl}}{E\pi R^2}\frac{\lambda_{B1} + \lambda_{B2}}{2} \tag{11}$$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{2E\pi R^2}{(m + (2/3)m_{cyl})H}} \tag{12}$$