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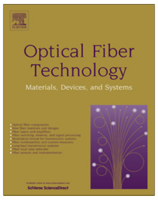

Study on a fiber Bragg grating accelerometer based on compliant cylinder

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ABSTRACT

A fiber Bragg grating (FBG) accelerometer based on a compliant cylinder is proposed and experimentally demonstrated in this paper. The accelerometer contains four parts, compliant cylinder, FBG, inertial mass, shell. In this design, the FBG is placed along the axis of the compliant cylinder, the material of the compliant cylinder is two-component vulcanized silicone rubber. The principle of the FBG accelerometer was analyzed theoretically. The amplitude–frequency responsivity, linear response and temperature characteristics of the sensor were studied by experiment. Experimental results show that the sensor has a broad flat frequency range from 30 to 300 Hz, and the sensitivity of the accelerometer is 42.7 pm/G with a linearity of 0.999. The applicable temperature range of the acceleration sensor at least more than 150.0 °C, and the dynamic range is 76 dB, making it as a good candidate for the downhole seismic signal measurement.

1. Introduction

In recent years, micro-seismic monitoring technology is an important new technology in the field of low permeability reservoir fracturing and mining engineering, the main purpose of the technology is through the sensor to monitor the underground micro-seismic events [1,2]. Therefore, the performance of the sensor affects the accuracy of the whole exploration results. Traditional accelerometers are usually piezo-resistive type, piezoelectric type, etc. [3], however, these accelerometers also suffer from limitation in space and time, which are difficult in satisfying the needs of large range monitoring. Compared with conventional sensors, FBG sensors have caught more attention because of their unique advantages, such as anti-electromagnetic interference, high temperature survivability, wide dynamic range, ease of multiplexing, amiability to harsh environment conditions [4–7]. As a result, the FBG sensor is extremely being developed rapidly at present.

Polymer optical fiber (POF) FBGs and Silica FBGs are usually used in the design of the accelerometers, POFs have several advantages compared to silica fiber, such as which can be used for clinical applications, POFs have the high failure strain and the low Young's modulus. This fact, together with the issue of high loss and low operating temperature, has been hindering the application of the polymer FBGs [8]. For example in [9] both silica and polymer FBG accelerometers were demonstrated with a very high resonance frequency of 3 kHz, however, the sensitivity of the sensor is relatively small.

Traditionally, silica FBGs were used because of their low loss and high operation temperature, a type FBG accelerometer with an integrative matrix structure was proposed in 2015 [10], sensitivity higher than 200 pm/G and the natural frequency larger than 3000 Hz can be obtained separately, but both cannot be achieved simultaneously, such as the sensitivity as 13.82 pm/G at 100 Hz, 14.64 pm/G at 200 Hz. Li et al. [11] demonstrated a very sensitive FBG accelerometer using transverse forces, the sensitivities 1.333 and 0.634 nm/G were achieved, but the acceleration measurement range only from 0.1 to 0.4 G, and the natural frequency is only 25 Hz. Zhang et al. [12] proposed a flextensional FBG-based accelerometer, the sensitivity can be as high as 410.7 pm/G, the applicable frequency range is only from 1 to 10 Hz. A double FBGs accelerometer based on an organic double-semicircle cantilever was proposed and experimentally demonstrated [13], the accelerometer provides a high sensitivity of 1296 pm/G and a frequency range from 0 to 25 Hz. An intensity-modulated optical fiber accelerometer was proposed by using the FBG incorporating a biconical fiber taper [14], the sensitivity of the sensor is 4.85 nW/G with a frequency up to 20 Hz, the intensity demodulation is easy to interference by external environmental. As in [15], a novel FBG

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accelerometer based on the diaphragm was proposed, the frequency flat response range from 10 to 200 Hz, with a sensitivity of 36.6 pm/G. A vibration accelerometer with a fully metalized package based on metal-coated FBG is investigated [16], but the packaging technique is tricky and the cost is very high. Weng et al. [17] reported a FBG vibration sensor based a flat diaphragm and two L-shaped rigid cantilevers beams with the method of two-dot coating encapsulation FBG, the sensitivity is 100 pm/G in the frequency response range 10–120 Hz, but the sensor structure is more complicated. A modified cantilever beam based FBG sensor accelerometer was theoretically modeled and designed [18], which can sense vibrations of extremely low intensity frequency (up to 5 Hz) and vibration (up to 0.01 G), however, the flatness of the sensitivity is very poor in different frequency band. Berkoff and Kersey [19] put the FBG embed in flexible rubber material from the side, the FBG can realize the acceleration signal measurement by sensing the lateral deformation of rubber material, it showed an extremely high resonant frequency of 2000 Hz and the sensitivity is 135 pm/G, but the cross-axis sensitivity is very large and it did not discuss the applicable temperature range. A high-performance compact vibration sensor based on FBG is designed [20], the acceleration sensitivity is about 30 pm/g in the frequency range of 10–250 Hz.

In this paper, a FBG accelerometer based on compliant cylinder is designed and manufactured. The FBG is a silica FBG, the material of the compliant cylinder is two-component vulcanized silicone rubber, which worked stably and availably. The FBG is placed along the axis of the compliant cylinder, which can reduce the cross-sensitivity, at the same time, it can protect the FBG from being damaged. Experimental results show that the sensor has a broad flat frequency range from 30 to 300 Hz, the corresponding sensitivity of the accelerometer is 42.7 pm/G with a linearity of 0.999, and the operating temperature of the sensor can be applied more than 150 °C. Compared with the previously mentioned accelerometers, this accelerometer not only has a wider frequency can be used, but also has a very high sensitivity. In addition, this sensor has the advantages of simple in structure, easy to encapsulate and can satisfy the detection requirements of micro-seismic technology.

2. Experimental setup and principle of operation

The schematic structure of the sensor is shown in Fig. 1. One end of the compliant cylinder is fixed on the base, the other end is combined with inertial mass. The FBG is placed along the axis of the compliant cylinder, and the material of the compliant cylinder is two-component vulcanized silicone rubber, the compliant cylinder is solid. The base is fixed on the vibration source, when subjected to external excitation signal, the base will be vibration with the measured object, which will cause the mass to vibrate. Under the effect of the inertia force, compliant cylinder will produce contraction and elongation which leading to center wavelength of the FBG change. So we can measure the wavelength shift of the FBG to detect the acceleration.

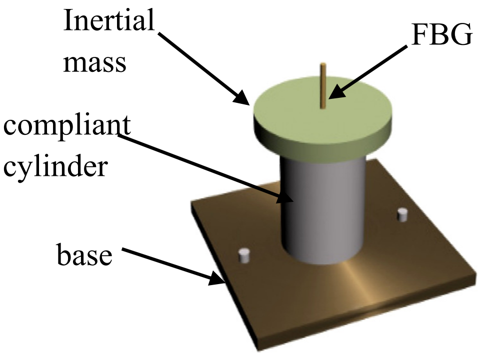

Fig. 1. Sensing model.

When the acceleration sensor is excited by the vertical direction signal, defined as a, by Newton's second and Hooke's law we can get

$$a = \frac{F}{M_{eff}} = \frac{K_{eff}\Delta L}{M_{eff}} \tag{1}$$

where ΔL is the variation of the FBG length, M_{eff} is the equivalent mass of elastic system, $M_{eff} = M_1 + \mu M_2$, where M_1 is the mass of the inertial mass, M_2 is the mass of the compliant cylinder, μ is proportional coefficient, we can get μ equal to 0.5 by gravity method. K_{eff} is the equivalent stiffness of the acceleration sensor, which can be expressed as

$$\begin{aligned} K_{eff} = K_1 + K_2 &= \frac{\pi E_1 d_1^2}{4L} + \frac{\pi E_2 d_2^2}{4L} \\ &= \frac{\pi}{4L}\left(E_1 d_1^2 + E_2 d_2^2\right) \end{aligned} \tag{2}$$

where L is the length of compliant cylinder, d_1 and d_2 are the diameter of the compliant cylinder and the fiber, respectively. E_1 and E_2 are the Young's modulus of the compliant cylinder and the fiber, respectively. When the strain of applied on the FBG is homogeneous and isotropic, the center wavelength shift $\Delta\lambda_B$ satisfies the equation [21]

$$\Delta\lambda_B = \lambda_B(1 - P_e)\varepsilon \tag{3}$$

In the Eq. (3), λ_B is the center wavelength of FBG, P_e is the effective elasto-optical coefficient, ε is the axial strain of FBG and based on the FBG sensing principle it can be defined as $\varepsilon = \frac{\Delta L}{L}$.

The sensitivity coefficient S of FBG acceleration sensor is defined as the FBG center wavelength shift caused by the unit of acceleration, it can be calculated as

$$S = \frac{\Delta\lambda_B}{a} = \beta\frac{(1 - P_e)m\lambda_B}{K_{eff}L} \tag{4}$$

where β is the strain coupling coefficient between FBG and compliant cylinder.

According to the mechanics model of the sensor and the single degree of freedom motion equation of simple harmonic oscillator, the natural frequency f_n of the FBG sensor can be expressed as

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K_{eff}}{M_{eff}}} \tag{5}$$

It can be seen from Eqs. (4) and (5) that the natural frequency will decrease when increase sensitivity, when increasing the natural frequency the sensitivity will decrease. Natural frequency and sensitivity are two important parameters of the FBG acceleration sensor, which determines its application field.

Table 1 gives all the physical parameters of the FBG vibration sensor. Through the parameter in the table we can calculate the

Table 1
The parameters of the vibration sensor.

Parameters	Value
E_1	3.9×10^6 Pa
E_2	7.3×10^{10} Pa
d_1	19 mm
d_2	125 μm
λ_B	1549.51 nm
P_e	0.22
L	26 mm
M_1	9 g
M_2	10 g