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Temperature-independent acceleration measurement with a strain-chirped fiber Bragg grating

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A novel fiber optic accelerometer is proposed and demonstrated. The sensing mechanism is based on the measurement of bandwidth and optical power of a strain-chirped fiber Bragg grating (FBG). Experimental results show that 3-dB bandwidth and reflected optical power of the strain-chirped FBG responds to acceleration sensitively. The achieved sensitivities are up to 0.4 nm/g and 4.57 μW/g respectively in the linear range. Furthermore, this sensor is very cost-effective and inherently insensitive to temperature due to the simple demodulation method.

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Keywords: Fiber Bragg grating (FBG), Accelerometer, Simply-supported beam, Temperature insensitive

1. Introduction

Optical fiber Bragg gratings (FBGs) have attracted considerable interests in various fiber optic sensor implementations for the past two decades. A great deal of FBG based transducers have been designed to deal with measurands such as strain, temperature [1], pressure [2,3], displacement [4,5], curvature [6], acceleration [7,8,9], etc. In 1996, Berkoff reported a fiber optic accelerometer by embedding a FBG in a layer of compliant material, which is supported by a rigid base plate and covered by a mass [8]. Another design was realized by using a concentrated mass welded between two thin parallel plates and fixing a FBG at the bottom surface of the lower plate [9]. These two designs are based on the measurement of acceleration-induced Bragg wavelength shift of the sensing FBGs, which, however, are also sensitive to temperature. Temperature compensation elements are needed to eliminate the temperature cross-sensitivity of the reported accelerometers. That will add to the cost and complexity of the sensor system.

In this paper, a novel FBG accelerometer is designed and presented, which encodes the acceleration signal into the changes of bandwidth and optical power of the sensing FBG. The additional advantage of the proposed accelerometer is temperature independent because the temperature only changes the central Bragg wavelength, but unaffects the bandwidth and reflected power of the FBG. Experimental results show that 3-dB bandwidth of the FBG responded linearly to the acceleration with a large range up to 8 g while the reflected optical power responded with a linear range of 4g. The relatively lower linear range of optical power is due to the reflectivity decay of the FBG when the bandwidth increases. The achieved sensitivities are 0.4 nm/g and 4.57 μW/g, respectively.

2. Design and principle

The proposed FBG accelerometer is based on a simply-supported beam structure, as shown in Fig. 1. An initially-uniform FBG was glued in a slant direction onto the lateral surface at the center of the beam. Two masses were fixed respectively on the top and bottom surfaces in the middle of the beam to sense the variation of the acceleration in the vertical direction. The masses are designed into cylindrical shape to reduce their unfavorable effects on the bending of the beam. Once the beam is bent by the weight and acceleration-caused force of the weights, it introduces a nonuniform strain filed along the length of the sensing FBG. Therefore, the period of the FBG become chirped. The bandwidth and reflected optical power changed accordingly. By monitoring these two parameters, we can determine the acceleration.

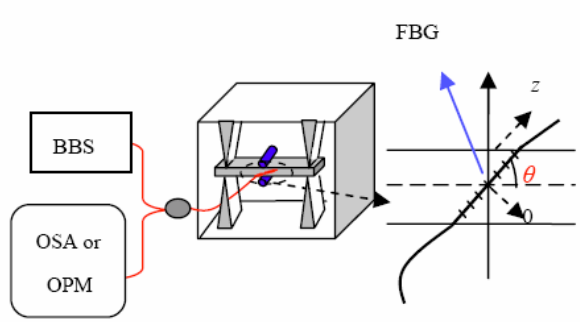


Fig. 1. Schematic diagram of the proposed FBG accelerometer system. BBS, broadband light source; OSA, optical spectrum analyzer; OPM, optical power meter.

When the sensor system is subjected to a vertical acceleration, denoted by *a,* the generated force applied to the beam is *ma*, where *m* is the sum of two added masses. The Bragg wavelength shift $\Delta\lambda_B$ of a segment of FBG at different position has the following relationship with the axial strain ε_{ax}

$$\Delta\lambda_B / \lambda_B = (1 - p_e)\varepsilon_{ax} \qquad (1)$$

where λ_B is the strain-free Bragg wavelength of the FBG, $p_e \approx 0.22$ is the effective elastic-optic coefficient of the fiber. According to the theory of material mechanics, a linearly-changed strain is introduced on the lateral surface of the beam along the length direction when the beam is bent. It can be described by [10]

$$\varepsilon(z) = kz \qquad (2)$$

where k is the curvature of the neutral layer of the beam, and z ($-0.5h \le z \le 0.5h$, h is the thickness of the beam) is the vertical axis of the beam with its zero point located at the neutral layer of the beam. Since the FBG was glued around the center of the beam and it is much shorter than the beam, the curvature of the beam is assumed the same along the whole FBG. The curvature can be expressed as

$$k = m(a + g)L / 4EI \qquad (3)$$

where g is the gravitational acceleration, E and L are Young's modulus and length of the beam, respectively. $I=bh^3/12$ is the cross-section moment of inertia of the beam, where b is the width of the beam. The mass of the beam is much smaller compare with the total mass m, so it is ignored in the theoretical analysis.

Since the FBG was glued in a slant direction onto the lateral surface of the beam, the strain along the FBG can be expressed by [10]

$$\varepsilon_{ax}(z) = \eta kz\cos(\theta) \qquad (4)$$

where η ($0 \le \eta \le 1$) is the transfer efficiency of strain from the beam to the grating, θ is the angle between the axis of the FBG and the neutral layer of the beam. When the beam is bent, therefore, the FBG will be linearly chirped. If define an x axis along the length direction of the FBG with its zero point located at the neutral layer of the beam. By considering $z=x\sin\theta$, the strain along the grating can be rewritten as

$$\varepsilon_{ax}(x) = \frac{1}{2}\eta kx\sin(2\theta) \qquad (5)$$

From Eq. (1) to Eq. (5), the bandwidth of the FBG under acceleration-induced strain can be written as

$$\begin{aligned}\Delta\lambda_{chirp} &= \Delta\lambda_{c0} + \lambda_B(1 - p_e)[\varepsilon_{ax}^{\max}(x) - \varepsilon_{ax}^{\min}(x)] \\ &= \Delta\lambda_{c0} + \eta L\lambda_B ma(1 - p_e)\sin(2\theta)l / 8EI\end{aligned} \qquad (6)$$

where $\Delta\lambda_{c0}=\eta\lambda_B mglL(1-p_e)\sin(2\theta)/8EI$ is the reflected spectral bandwidth for a=0 g, $\varepsilon_{ax}^{\max}$ and $\varepsilon_{ax}^{\min}$ are the axial strain at the two endpoints of the grating and l is the length of the grating. Therefore, bandwidth of the strain -chirped FBG will be changed by the acceleration. By substituting Eq. (3) into Eq. (6). It can be written as

$$\Delta\lambda_{chirp} = \Delta\lambda_{ch0} + A \times a \qquad (7)$$

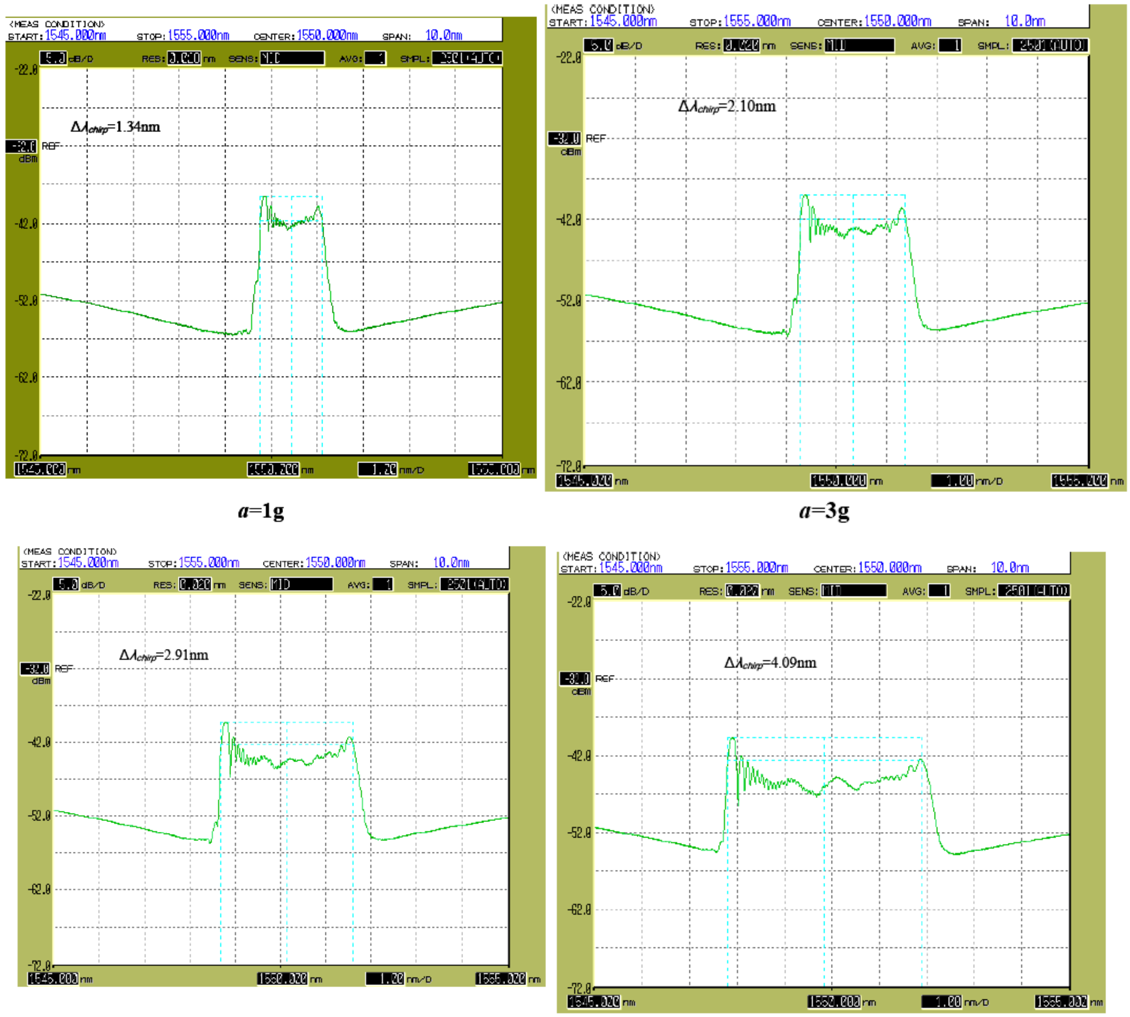
where $A=\eta m\lambda_B Ll(1-p_e)\sin(2\theta)/8EI$ is a constant.

It can be seen from Eq. (7) that the bandwidth of the FBG is a linear function of the applied acceleration, so acceleration can be determined by monitoring the bandwidth of the FBG. Furthermore, the reflected optical power of the strain-chirped FBG changes with the bandwidth accordingly, that allows another demodulation method by measuring the optical power reflected by the FBG. In this case, the accelerometer will be intensity-modulated and the cost will go down since only optical power meter (or photodetector) is needed for signal processing.

3. Experimental results and discussions

The schematic diagram of the experimental system for acceleration measurement is shown in Fig. 1. The FBG was written into a hydrogen -loaded single-mode fiber (SMF) using phase -mask method. It is 3-cm long, with a high reflectivity of 45 dB at 1550.56 nm, and a narrow 3-dB bandwidth of 0.27 nm. The simply-supported beam is 15-cm long, with a width of 6 mm, thickness of 5.5 mm. The total mass of two masses is 0.1 kg. Due to the masses induced beam deflection, the 3-dB bandwidth at a = 0 g, $\Delta\lambda_{ch0}$ became 0.88 nm. The angle θ between the axis of the FBG and the natural layer of the beam is 12°. A broadband light source (BBS) and an optical spectrum analyzer (OSA) or an optical power meter (OPM) were used, collaborating with an optical fiber coupler, to measure the optical spectrum or optical power of the sensing FBG.

Fig. 2 shows four reflective spectra of the FBG accelerometer, which were measured at four different accelerations of 1 g, 3 g, 5 g and 8 g, respectively. The corresponding 3-dB bandwidths are 1.34 nm, 2.10 nm, 2.91 nm and 4.09 nm for a=1 g, 3 g, 5 g and 8 g, respectively. The measurement range can be up to 8 g.



***a*=1g** ***a*=3g**

***a*=5g** ***a*=8g**

Fig. 2. Measured reflection spectra of the FBG under various acceleration of a=1g, 3g, 5g and 8g.

Fig. 3 shows the measured 3-dB bandwidth and center wavelength shift of the FBG against acceleration. The bandwidth-acceleration curve shows a high sensitivity of 0.4 nm/g with good linearity of R^2=0.999, while the maximum Bragg wavelength shift is only 0.32 nm with the acceleration range up to 8 g. The measurement resolution is 0.05 g which is limited by the OSA with the wavelength resolution of 0.02 nm. It is notable that the sensitivity and resolution of the accelerometer can be easily increased by either using a heavier weight or optimizing physical parameters of the simply-supported beam.

Fig. 4 shows the measured reflected optical power of the FBG against applied acceleration. The optical power-acceleration curve shows a maximum sensitivity of 4.57 μW/g can be achieved. It is obvious that the variation of reflected power is not linear when the acceleration exceeds 4 g because the reflectivity of the FBG was reduced rapidly. A longer or stronger FBG may help to enlarge the linear response range in power-detection method.

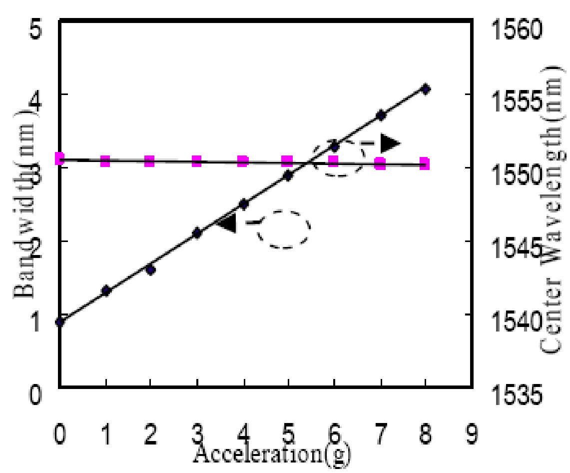


Fig. 3. 3-dB bandwidth and center wavelength versus acceleration.

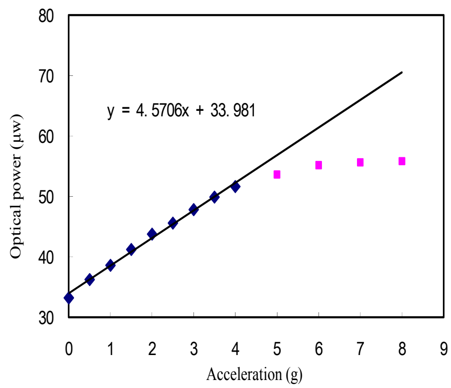


Fig. 4. The optical power versus acceleration.

A problem of common FBG-based sensors is the thermal crosstalk because FBG is inherently sensitive to both temperature and strain. The proposed FBG accelerometer can overcome this problem by measuring the bandwidth and reflected optical power of the FBG because temperature only induces Bragg wavelength shift but doesn't affect the bandwidth of the FBG. Temperature effect on the FBG accelerometer was evaluated by placing it inside a temperature-controllable oven. The 3-dB bandwidth and reflected optical power of the FBG were measured when the temperature was varied from 5 ºC to 45 ºC. As shown in Fig. 5, a maximum bandwidth variation of ±8 pm and optical power variation of ± 10 pW were recorded, which may be mainly caused by the vibration of the fan in the oven. The results showed that this accelerometer is insensitive to temperature.

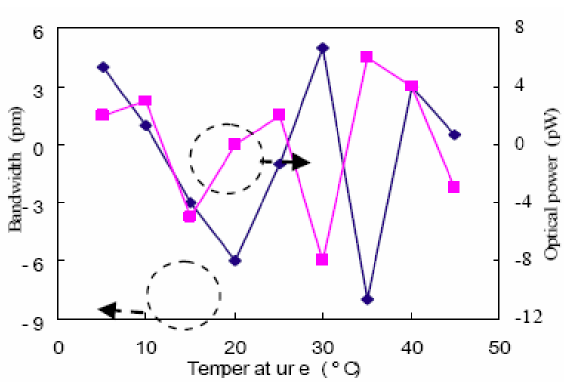


Fig.5. Change in bandwidth of the FBG accelerometer versus temperature at a constant acceleration.

4. Conclusions

A novel temperature-independent fiber -optic accelerometer with a strain-chirped FBG has been proposed. Experimental results show that 3-dB bandwidth of the FBG responded linearly to acceleration within a range up to 8 g while the reflected optical power with a linear range up to 4 g. The achieved sensitivities are up to 0.4 nm/g and 4.57 μW/g for measurements of reflected bandwidth and optical power, respectively. The sensitivity of the sensor can be improved by either using a heavier mass or optimizing physical parameters of the simply-supported beam. The power detection method reduces the cost and complexity of the sensor system. The proposed FBG accelerometer is a promising candidate for practical acceleration measurement.

Acknowledgement

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