Temperature-Independent Fiber Bragg Grating Acceleration Sensor

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ABSTRACT

An acceleration sensor based on measurement of the reflection bandwidth of a single fiber Bragg grating (FBG) is presented. The FBG is glued in a slanted direction onto the lateral surface at the center of the beam. Two weights were fixed respectively on the upper and lower surfaces in the middle of the beam to sense the variation of the acceleration in the vertical direction. Preliminary experimental results indicate that when the acceleration was increased, the 3-dB bandwidth of the FBG responded linearly from zero to 8 g, with very low temperature dependence. The measurement sensitivity and resolution are 0.4 nm/g and 0.05 g, respectively.

Keywords: Fiber Bragg gratings (FBGs), acceleration sensors, cross sensitivity

1. INTRODUCTION

Optical fiber Bragg gratings (FBGs) have attracted considerable interest in various fiber-optics sensor implementations for the past two decades. Various transducers based on FBGs 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. The basic principle of FBG sensors is based on the modulation of the reflection wavelengths of FBGs in response to temperature and strain. However, the FBG is sensitive to both temperature and strain, and is not able to distinguish them by itself. Several FBG acceleration sensors have been reported. In Ref. 8 is based on a FBG being embedded in a layer of compliant material, which is supported by a rigid base plate and covered by a mass. It can also be realized by making use of a concentrated mass element welded between two thin parallel plates with a FBG affixed to the bottom surface of the lower plate in Ref. 9. In the both reported designs, the motion of the mass when the transducers are subjected to acceleration will shift the Bragg wavelengths of the FBG elements, so that acceleration can be measured. They both based on the demodulation of Bragg wavelength, which, however, is sensitive to temperature thus temperature compensation is needed in some practical applications. That will add to system cost and complexity.

In this paper, a simple FBG acceleration sensor design is proposed, which encodes the sensing signal into the reflected bandwidth of a single FBG. The most important advantage is that the sensor is temperature independent because temperature only changes the central Bragg wavelength, but not the bandwidth of the FBG. Experimental results indicate that the bandwidth response range up to 8 g with a high sensitivity of 0.4 nm/g can be achieved. The measurement resolution, based on the wavelength resolution, 0.02 nm, of the employed optical spectrum analyzer (OSA), is 0.05 g.

2. DESIGN AND PRINCIPLE

As shown in Fig. 1, the proposed FBG acceleration sensor is based on a simply supported beam with a FBG glued in a slant direction onto the lateral surface at the center of the beam. Two weights were fixed respectively on the upper and lower surfaces in the middle of the beam to sense the variation of the acceleration in the vertical direction. They are cylindrically-shaped in order to reduce their effects on the bending of the simply supported beam. Once the acceleration is changed, a force produced by the weights will apply on the beam to change its deflection (or curvature). That will introduce a linearly-changed strain filed along the length of the attached FBG and make it chirped. As a result, the reflected bandwidth of the FBG will change with the acceleration.

Photonics and Optoelectronics Meetings (POEM) 2009: Fiber Optics Communication and Sensors,
edited by Dieter Stefan Jäger, Hequan Wu, Shuisheng Jian, Desheng Jiang, Deming Liu, Proc. of SPIE
Vol. 7514, 7514100 © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.840687

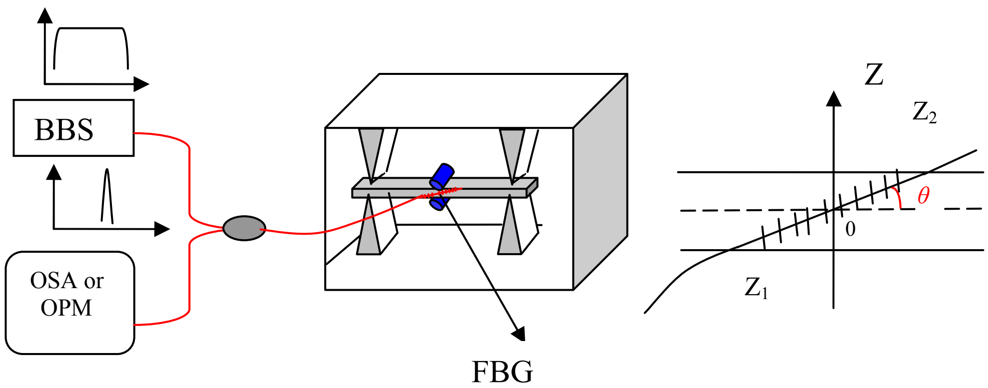


Fig.1 Design and measurement system of the proposed accelerometer based on a strain-chirped FBG. BBS, broadband laser source; OSA, optical spectrum analyzer; OPM, optical power meter.

Since the mass of the beam is much less than that of the weights, it is ignored in the following analysis. When the sensor is subjected to a vertical acceleration a, the additional force applied to the beam is ma, where m is the mass of two weights. According to the theory of material mechanics, when the beam is bent, a linearly changed strain field generated on the lateral surface of the beam. It can be described by

$$\varepsilon(z) = kz \tag{1}$$

where 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. k is the curvature at the center of the simply supported beam, given by

$$k = maL/4EI \tag{2}$$

where E and L are Young's modulus and length of the beam, respectively. $I = bh^3/12$ is the cross-section moment of inertia, L and b are the length and width of the beam, respectively. If the FBG is much shorter than the simply supported beam, the curvature for the beam section where the FBG was attached can be regarded as the same, so the strain transferred to FBG can be expressed as

$$\varepsilon_{ax}(z) = \eta kz\cos(\theta) \tag{3}$$

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 natural layer of the beam.

Studies have shown that the Bragg reflection wavelength of a FBG and its axial strain ε_{ax} have the following linear relationship

$$\Delta\lambda/\lambda_B = (1-p_e)\varepsilon_{ax}(z) \tag{4}$$

where λ_B is the strain-free Bragg wavelength of the FBG, p_e=0.22 is the effective elastic-optic coefficient of the grating.

The bandwidth of the FBG will be changed by the nonuniform strain distribution as shown by Eqs. (3) and (4). It can be written as

$$\Delta\lambda_{chirp} = \lambda_B(1-p_e)[\varepsilon_{ax}(z_2) - \varepsilon_{ax}(z_1)] = A \times a \tag{5}$$

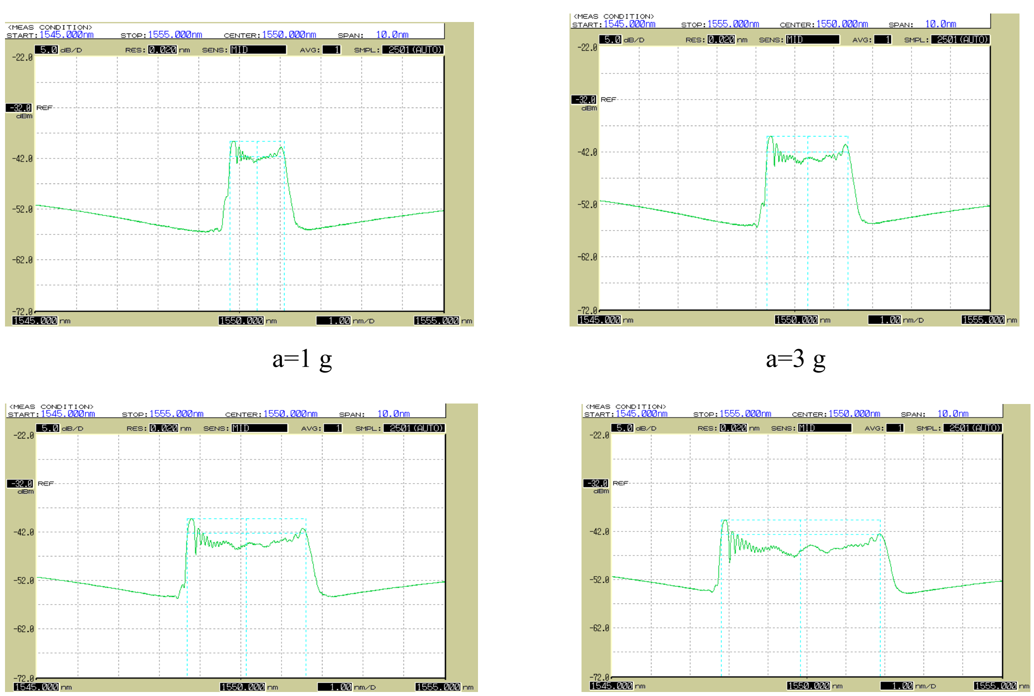
where $A = \eta m \lambda_B Ll(1 - p_e)\sin(2\theta)/8EI$ is a constant and l is the length of the FBG.

A common problem of using FBG-based sensors is the thermal crosstalk. This is because FBGs are sensitive to both temperature and strain. The proposed FBG acceleration sensor overcomes this problem owing to the independence of the bandwidth of the FBG to temperature. Since the temperature induced Bragg wavelength shifts for all grating segments are the same, bandwidth of the FBG is insensitive to temperature, although the reflection centre wavelength is changed.

3. EXPERIMENTS AND RESULTS

The schematic diagram of the experimental system for acceleration sensor is shown in Fig1. The FBG was written into a hydrogen-loaded single-mode fiber (SMF) using the phase-mask method. For verification of the proposed sensor design, a 3-cm long FBG was glued in a slant direction onto the lateral surface of a simply supported beam with length L =15 cm, width b =6 mm, and thickness h =5.5 mm. The FBG has a high reflectivity of 45 dB at 1550.56 nm, and a 3-dB bandwidth of 0.8752 nm for a = 0 g. The angle θ between the axis of the FBG and the natural layer of the beam is 12°. The weight of the two weights which were fixed respectively on the upper and lower surfaces in the middle of the beam is 0.1 kg. A broad band laser source (BBS) and an OSA or an OPM were used, interacting with an optical fiber coupler, to measure the optical spectrum and the optical power of the sensing FBG.

Fig.2 shows four reflective spectra of the FBG acceleration sensor, which were measured at four different accelerations of 1 g, 3 g, 5 g and 8 g, respectively. The measurement range can be up to 8 g. The measurement resolution, based on the wavelength resolution, 0.02 nm, of the employed OSA, is 0.05 g. It is notable that the sensitivity and resolution of the acceleration sensor can be easily increased by either using a heavier weight or optimizing physical parameters of the simply supported beam. It can be seen that the tops of the reflection spectra are not very flat, that may be because the FBG and the beam are not made from the same material.



a=1 g a=3 g

a=5 g a=8 g

Fig.2.Measured reflection spectra of the FBG under various acceleration of a=1 g, 3 g, 5 g and 8 g. The corresponding 3-dB bandwidths of a=1 g, 3 g, 5 g and 8 g are 1.335 nm, 2.0952 nm, 2.9065 nm and 4.0875 nm, respectively.

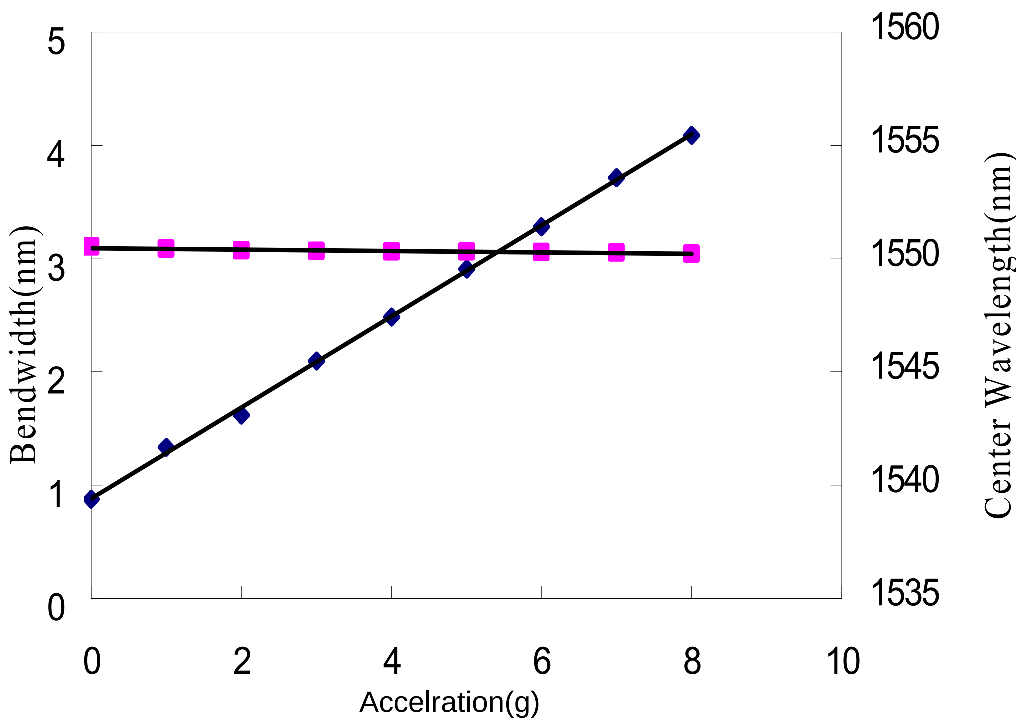


Fig.3.The 3-dB bandwidth variation and center wavelength shift versus acceleration.

Fig.3 shows the measured reflection bandwidth 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. The central wavelength of FBG's reflection spectrum changes 0.32 nm. The experimental results are smaller than the theoretical value. It means small part of the strain was lost during transfer from the beam to the fiber, due to the non-ideal gluing bonding between them. And the curvature reduction at the both ends of the FBG as compared with that of the center, due to bending property of the simply supported beam, may also make this value smaller.

Typical temperature-wavelength shift coefficient of a FBG sensors is ~10 pm/ºC, so it is important to eliminate or reduce the thermal effect on this acceleration sensor. Temperature effect on the performance of the FBG acceleration sensor was evaluated by placing it inside an oven and changing the temperature. The bandwidth of the FBG was measured when the oven temperature was varied from 5 ºC to 45 ºC. The measured results are shown in Fig.4. Small bandwidth variation of ±8 pm was recorded, which was mainly caused by the vibration of the oven fan. This measurement result testified that the proposed acceleration sensor is not sensitive to temperature.

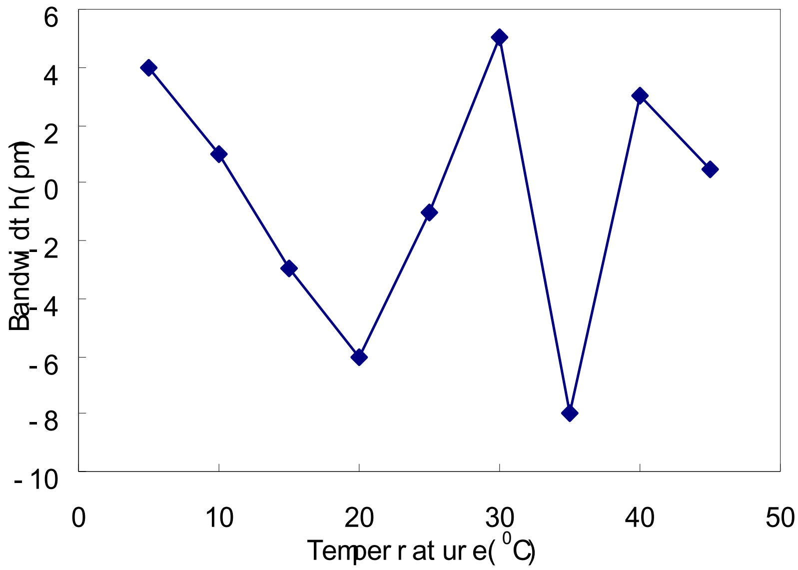


Fig.4 Change in bandwidth of the FBG acceleration sensor versus temperature at a constant acceleration.

4. CONCLUSIONS

A novel temperature-independent fiber-optic accelerometer with a strain-chirped FBG has been proposed. The FBG is glued in a slanted direction onto the lateral surface at the center of the beam. Two weights were fixed respectively on the upper and lower surfaces in the middle of the beam to sense the variation of the acceleration in the vertical direction. Large measuring range up to 8 g. with a high bandwidth sensitivity of 0.4 nm/g and resolution of 0.05 g was demonstrated. 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.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China under Grant No. 60807021 and the Natural Science Foundation of Zhejiang Province China under Grant No. R1080087.

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