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Temperature-insensitive accelerometer based on a strain-chirped FBG

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ABSTRACT

A novel accelerometer based on a strain-chirped optical fiber Bragg grating (FBG) is proposed. The FBG is glued in a slanted direction onto the lateral side of a right-angled triangle cantilever beam with a mass bonded on its free end. Vertical acceleration applied to the cantilever beam leads to a uniform bending along the beam length. As a result, the FBG is chirped and its reflection bandwidth changes linearly with the applied acceleration. A high sensitivity of 0.679 nm/g has been achieved in the experiment. This sensor is temperature insensitive, owning to the temperature-independence nature of reflection bandwidth of the FBG.

1. Introduction

Fiber Bragg gratings (FBGs) have attracted considerable interests in various fiber-optic sensor implementations for the past two decades. In addition to the well-known advantages of fiber-optic sensors such as electrically passive operation, immunity to RFI and EMI, high sensitivity, compact size and potentially low cost, FBG-based sensors have an inherent self-referencing capability and are easily multiplexed in a serial fashion along a single fiber. The success of FBG-based sensors on the measurement of strain has facilitated the modification of transducer designs that can deal with other measurands such as acceleration [1–5]. Previously reported accelerometers relied on the demodulation of reflected wavelength shift, but the wavelength shift is sensitive to temperature. Additional temperature compensation techniques are therefore necessary, which add to system cost and complexity.

In this paper, a novel temperature-insensitive accelerometer based on a strain-chirped FBG is proposed. The FBG is glued in a slanted direction onto the lateral side of a right-angled triangle cantilever beam with a mass bonded on its free end. Vertical acceleration applied to the cantilever beam leads to a uniform bending along the beam length. As a result, the FBG is chirped and its reflection bandwidth and power change linearly with the applied acceleration. Furthermore, this sensor is temperature insensitive, owning to the temperature-independence nature of reflection bandwidth of the FBG.

2. Design and principle

Fig. 1 shows the schematic diagram of the proposed FBG-based accelerometer. A 3-cm long FBG was glued in a slanted direction onto the lateral side of a right-angled triangle cantilever beam with length $L = 16.5$ cm, width at the fixed end $b_0 = 3$ cm, thickness $h = 0.5$ cm, and Young's modulus of material $E = 3.3 \times 10^9$ Pa. A mass was installed at the free end, with weight $m = 100$ g. The FBG was deeply written in a hydrogen-loaded photosensitive single-mode fiber with a scanning 244 nm UV laser beam using the phase-mask method. After fabrication, it was annealed at 100 °C for ∼15 h. The achieved FBG has a high reflectivity better than 30 dB, a central Bragg wavelength of 1556.10 nm, and a 3-dB spectral bandwidth of 0.154 nm. After the FBG was glued onto the lateral surface of the cantilever beam, the angle (θ) between the axis of the FBG and the neutral layer of the beam is 9.6°, which is changeable depending on the length of the FBG and the thickness of the cantilever beam. The cantilever beam was fixed in a frame for the convenience of accelerometer measurement.

When the cantilever beam is bent by applying a vertical acceleration on the sensor setup, the strain along the length of grating has a uniform gradient since the cantilever is a uniform-strength beam [6]. In this case, half of the grating is under a varying tension, whereas the other half is under a varying compression. The FBG is chirped by this strain field and its reflection spectrum is broadened with increase of acceleration. The strain on the neutral layer of the beam is zero; hence no change in wavelength happens to this segment of grating. If the center of the grating is located well to the neutral layer of the beam, the center wavelength of the grating may keep fixed during the accelerating process.

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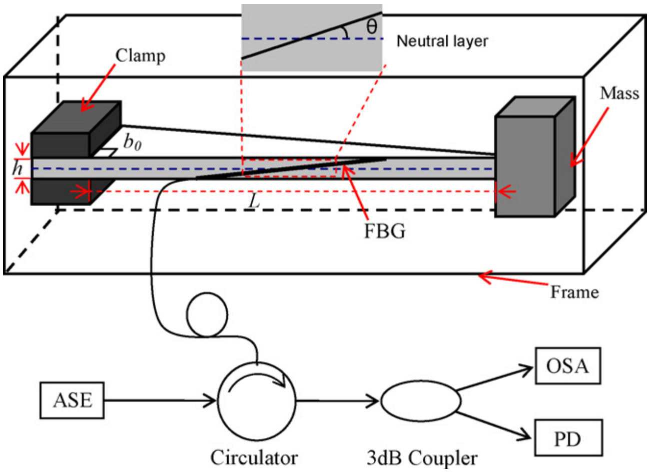

Fig. 1. Schematic diagram and experimental system of the proposed FBG accelerometer.

Based on the analysis previously reported by some of the authors in Ref. [6], the curvature of the cantilever beam, when the beam is bent, is uniform along its length due to the special triangle design. That ensures an equal variation in chirp rate along the FBG and finally helps to maintain a uniform reflectivity against wavelength for the reflection spectrum after the FBG is chirped significantly. The variation in the FBG's bandwidth, $\Delta\lambda_c$, is related to the vertical displacement, *f*, of the mass at the free end of the beam by [6]

$$\Delta\lambda_c = A_1 \times f, \tag{1}$$

where $A_1 \cong C(1-p_e)\lambda_{Bc}L_gL^{-2}\sin(2\theta)$ is a constant determined by the following parameters, C ($0<C<1$), a constant that represents the efficiency of the strain transfer from the beam to the grating; p_e, the effective photoelastic constant (~0.22) of the fiber material; λ_{Bc}, the central wavelength of the FBG; L_g, the length of the FBG; and L and θ which were afore assigned. When the cantilever beam is bent by applying a vertical acceleration a on the sensor setup, the mass will produces a vertical displacement on the beam. The acceleration, a, is related to the displacement of the mass by [7]

$$K \times f \approx m \times a, \tag{2}$$

where $K = Eb_0h^3/6L^3$, is the equivalent stiffness of the cantilever beam. So the bandwidth, $\Delta\lambda_c$, of the FBG under an applied acceleration of a, is given by

$$\Delta\lambda_c = A_2 \times a, \tag{3}$$

where $A_2 = 6C(1-p_e)\lambda_{Bc}L_gLm\sin(2\theta)/Eb_0h^3$ is a constant for a certain sensor setup. Due to the existence of the mass, the beam is bent even there is no acceleration and the reflected spectrum of the FBG has an initial bandwidth $\Delta\lambda_0$ of 0.721 nm. As $C=1$ (the ideal condition) is assumed, the calculated value of A_2 is 0.953 nm/g, based on related parameters of the experimental setup. It can be seen from Eq. (3) that the acceleration can be measured by detecting the reflected bandwidth.

It is important to note that the sensitivity of the sensor can be easily adjusted by changing values of the following parameters, b_0, L, h, L_g and the mass m. Provided that a broadband light source with flat output power in terms of wavelength is used as the light source, intensity-modulated acceleration measurement by monitoring the reflected optical power of the strain-chirped FBG is also obtainable. In that case, related studies show that a linear output signal can be achieved in a large measurement range based on the length and reflectivity of the used FBGs [8,9].

3. Experimental results and discussions

In the experiment, the sensor system was measured with directly applying forces to the mass to simulate the effect of acceleration changes since a real acceleration-controlled measurement system is not available. With different equivalent accelerations being applied on the sensor setup, the reflected spectrum of the FBG was measured by using a gain-flattened amplified spontaneous emission (ASE) source, an optical spectrum analyzer (OSA) with a resolution of 0.05 nm and a photodetector (PD). Fig. 2 shows the measured reflection spectra at different accelerations of 0 g, 2 g, 4 g, and 6 g. With increasing the acceleration, the bandwidth of the

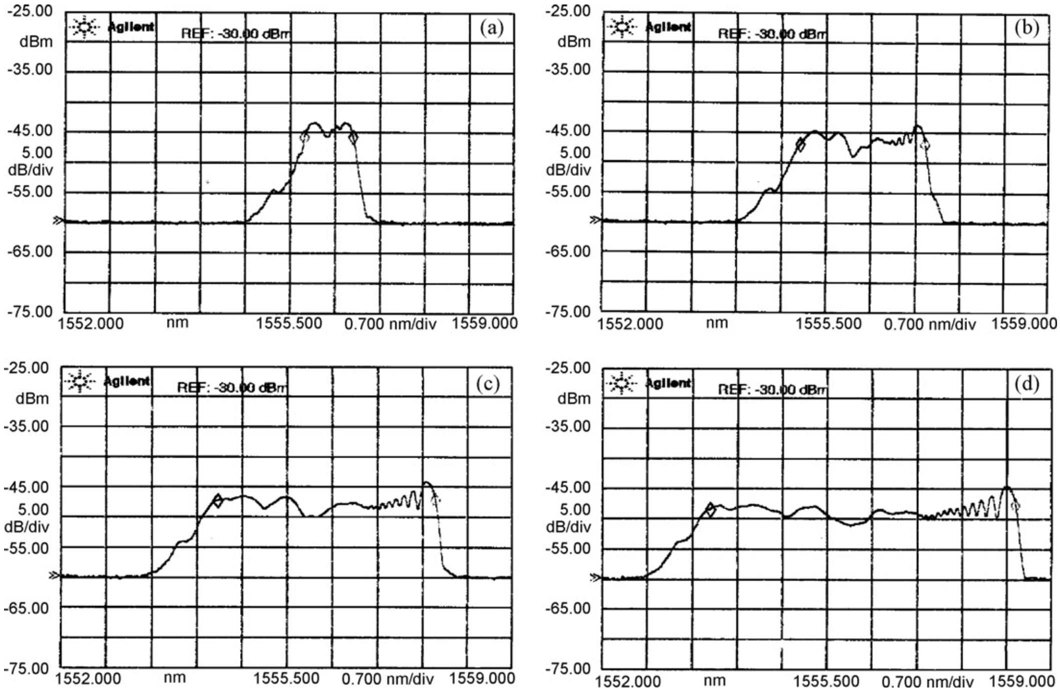

Fig. 2. Measured reflection spectra of the FBG under various accelerations of a = 0 g (a), 2 g (b), 4 g (c) and 6 g (d).

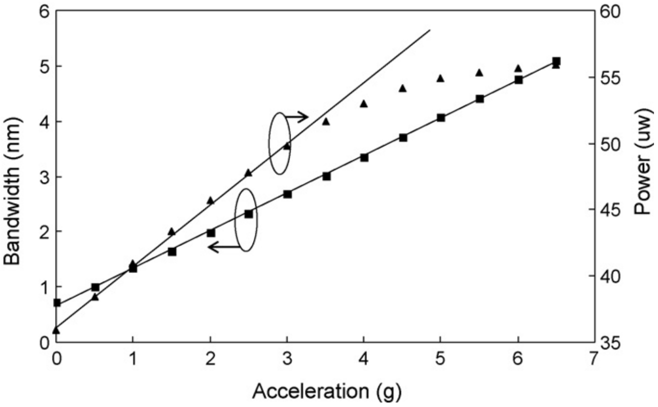

Fig. 3. Measured bandwidth and optical power versus acceleration for the accelerometer.

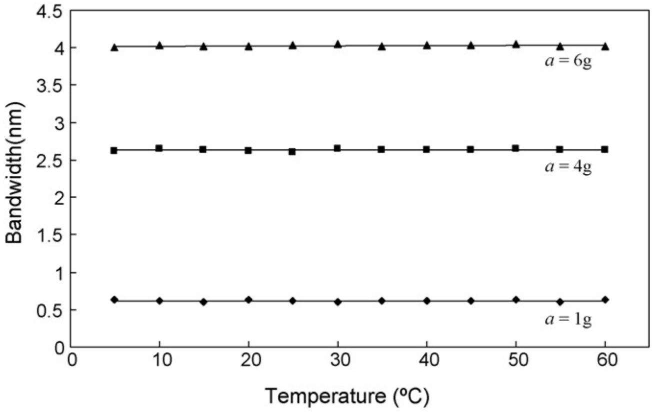

Fig. 4. Measured 3-dB bandwidth versus temperature.

reflected spectrum increases as a result of the acceleration-induced strain gradient chirp on the grating period. Although the reflectivity is reduced significantly and the tops of the reflection spectra are not quite flat, we managed to record the 3-dB bandwidth and reflection optical power. Better reflection spectrum can be achieved by using a longer FBG and/or improving the gluing quality of the FBG to the lateral surface of the cantilever beam.

The measured 3-dB bandwidth and reflected optical power versus the applied acceleration on the sensor setup are shown in Fig. 3. The achieved sensitivity is 0.679 nm/g, smaller than the theoretical value of 0.953 nm/g, indicating that the real strain transfer efficiency constant C is only 0.71, which can be improved by using a better adhesive or techniques such like making a groove on the beam surface to embed the FBG. The weight of the mass is critical to the sensitivity of the accelerometer. Using a heavier mass leads to a bigger sensitivity, but the measurement range of the acceleration will be reduced because there is a tradeoff between the two parameters. It is obvious that the variation in reflected power is not linear when the acceleration exceeded 3 g because of the obvious reduction in reflectivity of the FBG. A FBG with a longer length and a higher reflectivity will be helpful to increase the linear response range.

During the monitoring process, the measured maximum variation in the center wavelength is only 0.04 nm, which is neglectable and maybe caused by a small mismatch between the center of the FBG and the neutral layer of the cantilever beam, as well as variations of ambient temperature.

If the sensor is subjected to temperature variations, the Bragg wavelength will therefore shift as a result of the thermo-optic effect and the thermal expansion. However, this wavelength shift will not affect the reflected bandwidth and optical power signals. Measured results by putting the FBG accelerometer into an oven under different accelerations (vertical displacements) and varying the temperature are shown in Fig. 4. Small variations of 0.02 nm in the reflection bandwidth are mainly due to the vibration of the oven fan.

4. Conclusion

In this paper, a novel temperature-insensitive FBG accelerometer has been proposed. The FBG was glued in a slanted direction onto the lateral side of a right-angled triangle cantilever beam with a mass bonded on its free end. Vertical acceleration applied to the cantilever beam leads to a uniform bending along the beam length. As a result, the FBG is chirped and its reflection bandwidth changes linearly with the applied acceleration. In the experiment, a high sensitivity of 0.679 nm/g has been achieved with a large measurement range of 6.5 g.

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Biographies

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Ping Shum received the B. Eng. and PhD degrees in electronic and electrical engineering from of the University of Birmingham, UK, in 1991 and 1995, respectively. After PhD graduation, he stayed in the same university as an honorary postdoctoral research fellow. In 1996, he joined the Department of Electrical and Electronic Engineering, Hong Kong University. Since July 1997, Dr. P. Shum joined the Department of Electronic Engineering, Optoelectronics Research Centre, City University of Hong Kong. In 1999, Dr. Shum joined the School of Electrical and Electronic Engineering, Nanyang Technological University. Since 2002, he has been appointed as the Director of Network Technology Research Centre. He became a full professor in 2009. Prof. Shum has published more than 250 international journal and conference papers. His research interests are concerned with optical communications, nonlinear waveguide modeling, optical fiber sensors, photonic crystal fibers and WDM communication systems.