Intensity-modulated and temperature-insensitive fiber Bragg grating vibration sensor

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Abstract. An intensity-modulated, fiber Bragg grating (FBG) vibration sensor is proposed and experimentally demonstrated. An initially-uniform FBG is glued with a slanted direction onto the lateral surface of a simply-supported beam (SSB). A mass fixed in the middle of the beam transfers the vertical vibration to the deflection of the beam. Nouniform strain field generated by beam bending is applied along the FBG and makes it chirped. The sensing mechanism is based on the measurement of reflected optical power of a strain-chirped FBG. The optical power from the FBG is measured with a photodetector (PD) and an oscilloscope. A resistance strain gauge is used for the comparison purpose and good agreement is achieved. Furthermore, this sensor is cost-effective and inherently insensitive to temperature.

1. Introduction

Fiber Bragg grating (FBG) sensors have been studied for more than two decades. FBG sensors are very attractive because they have many advantages over conventional electrical sensors, such as high sensitivity, remote sensing, low loss transmission, light weight, chemical stability and immunity to electromagnetic interference. Besides, the intrinsic wavelength encoding gives the FBG sensors a multiplexing capability that greatly reduces cabling labor. Because of these intrinsic natures, FBG sensors have great potential to be applied to measurands of static and dynamic, such as temperature [1], pressure [2-4] and vibration [5-10]. FBG vibration sensors are extremely attractive in many industrial fields, such as mine safety monitoring, aerocraft and civil construction. Most of previously reported FBG-based vibration sensors are based on the measurement of Bragg wavelength shift of the sensing FBGs. But the FBG sensors based on wavelength demodulation have to monitor the reflection wavelength of FBG, so expensive wavelength measurement instrument are normally used. The measurement speed of wavelength measurement instrument is relatively low. On the other hand, Bragg wavelength shift of the sensing FBGs are also sensitive to temperature. Thus temperature compensation is needed when these reported vibration sensors are used in practical applications. That will add to the cost and complexity of the sensor system.

In this paper, a novel intensity-modulated, FBG-based vibration sensor is proposed and experimentally demonstrated. An initially-uniform FBG is glued with a slanted direction onto the lateral surface of a simply-supported beam (SSB). A mass fixed in the middle of the beam transfers the vertical vibration to the deflection of the beam. Nouniform strain field generated by beam bending is applied along the FBG and makes it chirped. The sensing mechanism is based on the measurement of reflected optical power of a strain-chirped FBG. The reflected optical power from the FBG is measured with a photodetector (PD) and an oscilloscope. A resistance strain gauge is used for the comparison purpose and good agreement is achieved. Furthermore, this sensor is very cost-effective and inherently insensitive to temperature.
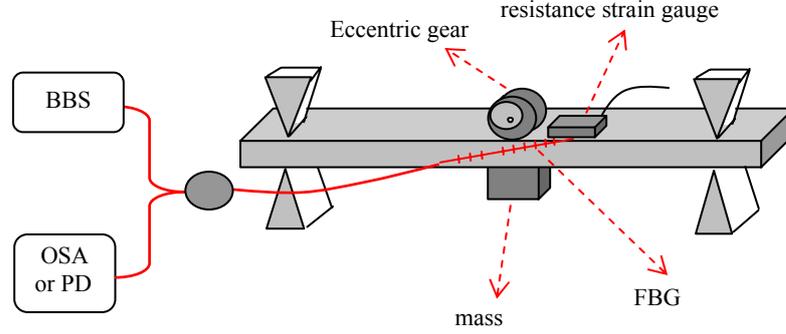
Figure 1. Schematic diagram and experimental system.

2. Principle

An initially-uniform FBG is glued with a slanted direction onto the lateral surface of the SSB as shown in Fig. 1. When the SSB is bent by applying a vertical vibration, strain gradient is formed along the length of the grating, and produces a linear variation in the grating pitch. In this case, half of the FBG is under varying tension whereas the other half is under a varying compression. The chirp rate of the FBG can be varied by bending the beam with different radius of curvature.

As the analysis previously reported in Ref. 11, if the grating is located exactly at the neutral layer of the beam, the induced strain and thus the Bragg wavelength shift of any two points on the grating, at equal distance but on opposite side from the center of the FBG, is equal in magnitude but opposite in sign. The reflection bandwidth of the chirped FBG, $\Delta\lambda_c$, is depended on the radius of curvature of the beam's neutral layer k and is given by [11]

$$
\begin{aligned}
\Delta\lambda_c &= \Delta\lambda_{max} - \Delta\lambda_{min} \\
&= C\lambda_B kl(1-p_e)\sin(2\theta)/2
\end{aligned}
\tag{1}
$$

where C $(0 < C < 1)$ is a constant that represents the efficiency of the strain transfer from the beam to the grating; λ_B is the strain-free Bragg wavelength of the FBG; l is the length of the grating; $p_e \approx 0.22$ is the effective elastic-optic coefficient of the fiber; and θ is the angle between the axis of the FBG and the neutral layer of the beam. Its radius of curvature is directly proportional to the deflection of the beam's center f, and is given by [11]

$$
k = 12f / L^2
\tag{2}
$$

where L is the distance between the two supporting points. When the SSB is bent, the deflection induced nouniform strain is applied along the sensing FBG and makes it chirped. Therefore, bandwidth of the strain-chirped FBG will be changed by the deflection of the beam's center. By substituting equation (2) into equation (1), it can be written as

$$
\Delta\lambda_c = \Delta\lambda_0 + A \times f
\tag{3}
$$

where $\Delta\lambda_0$ is the reflected bandwidth of the FBG when there is no variation; $A=6C\lambda_B l(1-p_e)\sin(2\theta)/L^2$ is a constant for the certain sensor.

According to equation (3), the bandwidth of the grating increases with the deflection and, consequently, the reflected optical power of FBG will increase as well. So by measuring the reflected optical power of the FBG can achieve intensity demodulation.
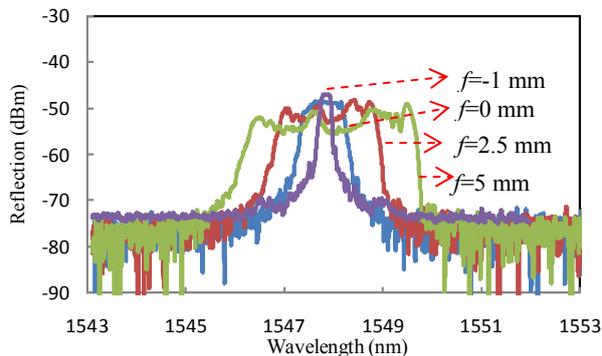
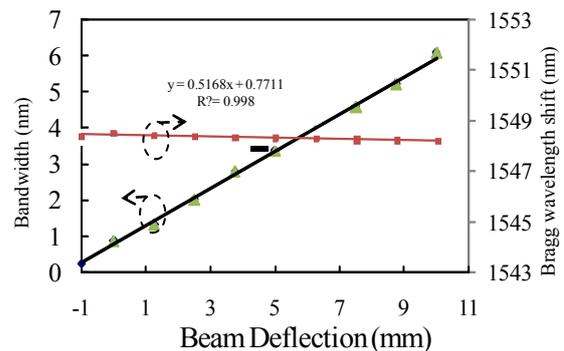**Figure 3**. Reflection spectrum of the chirped FBG for various deflections.

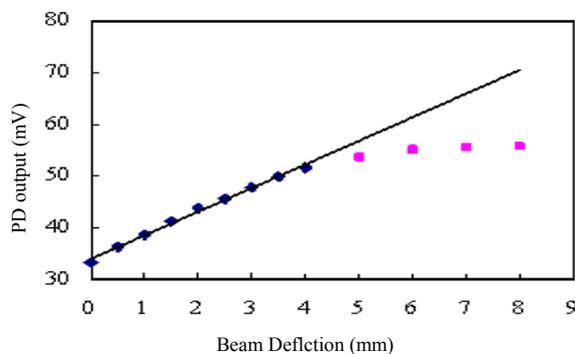**Figure 4**. 3-dB bandwidth and center wavelength shift versus the beam deflection.

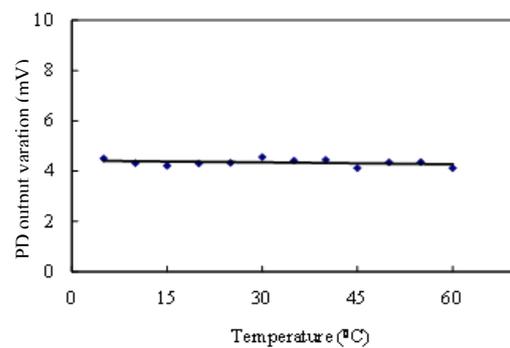**Figure 5.** Optical power versus beam deflection.

Figure 6. PD output variation versus temperature variation.

3. Experimental results and discussion

The schematic diagram of the experimental system for FBG-based vibration sensor is shown in Fig. 1, where both the FBG and a resistance strain gauge are mounted on the SSB. The FBG was written into a hydrogen-loaded single-mode fiber (SMF) using phase-mask method. After fabrication, it was annealed at 100 ºC for 15 hours. The achieved FBG is 3-cm long, with a high reflectivity of 45 dB at 1547.93 nm. The SSB is 20-cm long, with a width b of 6 mm, thickness h of 5.5 mm. The angle θ between the axis of the FBG and the natural layer of the beam is 15°. The eccentric gear with weight m = 100 g was installed at the middle of the SSB as a vibration generator. To achieve linear response of the FBG, it is necessary to fix the mass at the middle of the beam to make the FBG pre-chirped (or have an initial bandwidth $\Delta\lambda_0$=0.88 nm). In the experiment, the mass with weight of 100 g was used to produce an original deflection. A broadband light source (BBS) and an optical spectrum analyzer (OSA) or a PD were used, collaborating with an optical fiber coupler, to measure the optical spectrum or optical power of the sensing FBG.

3.1 Static Measurement

Experimental measurements of the chirped FBG's reflection spectra taken at different static beam deflections are shown in Fig. 3. It shows four reflective spectra, which were measured at different deflections of -1, 0, 2.5 and 5 mm, respectively. The corresponding 3-dB bandwidths are 0.25, 0.88, 2.02 and 3.38 nm, and the measured maximum variation in center wavelength is very small, less than 0.32 nm. It is obvious that the bandwidth of FBG spectrum varies with the beam deflection. The tops of the reflection spectra are not very flat due to nonuniform index modulation of the FBG and strain distribution. However, the bandwidth is varying in a linear manner within the measured range of beam deflection. Fig. 4 shows the 3-dB bandwidth and center wavelength versus the beam deflection for static measurement. It shows a static range of 11 mm and a changing rate of 0.52 nm/mm. Fig. 5 shows the measured reflected optical power of the FBG against the static beam deflection. It is obvious that the variation of reflected optical power is not linear when the beam deflection exceeds 4 mm 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.
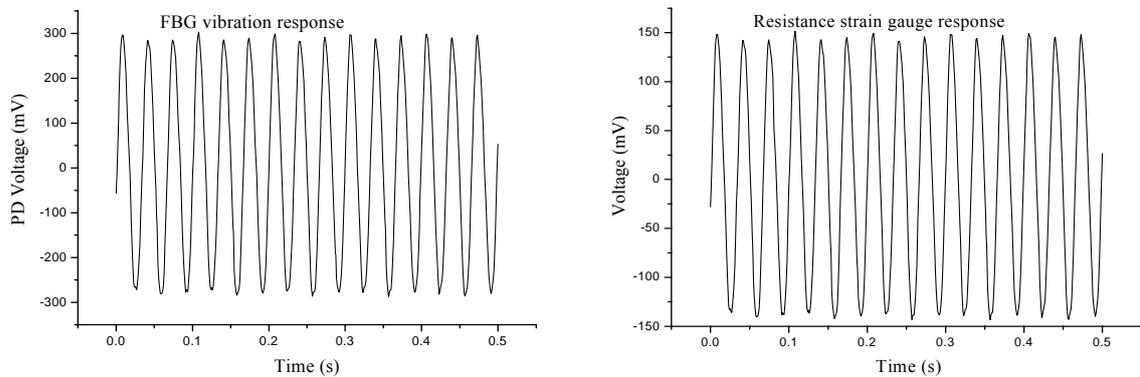
Figure 7. Power density spectrum of FBG vibration response and resistance gauge response.
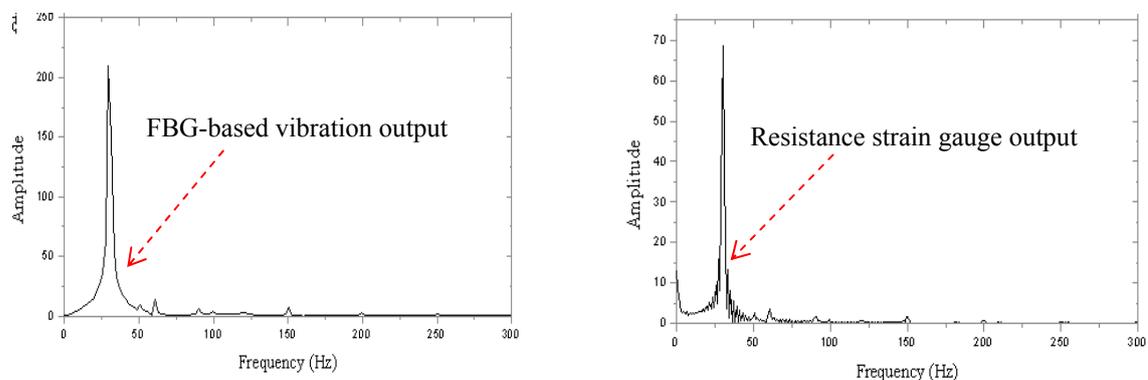

Figure 8. Frequency response spectra of FBG vibration output and resistance gauge output.

A common problem of FBG-based sensors is the thermal crosstalk because FBG is inherently sensitive to both temperature and strain. The proposed FBG vibration sensor can overcome this problem by measuring the reflected optical power of the FBG because temperature only induces Bragg wavelength shift but doesn't affect the optical power. Temperature effect on the FBG output is evaluated by placing the sensor setup inside a temperature-controllable oven. The optical power of the FBG is measured when the temperature is varied from 5 ºC to 60 ºC. As shown in Fig. 6, a maximum optical power variation of 5 mV is recorded, which may be mainly caused by the vibration of the fan in the oven.

3.2 Dynamic Measurement
Dynamic measurements are taken by installing the eccentric gear at the middle of the beam as the vibration source and monitoring the output signals of the FBG reflected optical power and the resistance strain gauge simultaneously. Assuming the output curve of the eccentric gear is sinusoidal wave, the output of FBG sensor will be sinusoidal curve as well. Vibration modal frequency can be analyzed from the fast Fourier transform (FFT) waveform of the frequency signal.

Fig. 7 shows the time signal waveforms of the FBG and the resistance strain gauge, respectively. The output traces of the two sensors agree with each other very well. The experimental data of both sensors were sampled as the records in 0.5 s and analyzed by using a computer. The vibration frequency of the eccentric gear is 29.75 Hz. The calculated frequency spectra of the output signals from both sensors using FFT method are shown in Fig. 8. The achieved vibration frequencies are 29.89 Hz and 30.27 Hz for the FBG and the resistance strain gauge, respectively. The measurement results are in good agreement.

4. Conclusion
A low cost fiber-optic sensor using a FBG element for detection of vibration has been proposed. An initially-uniform FBG has been glued with a slanted direction onto the lateral surface of the SSB. A mass fixed in the middle of the beam transfers the vertical vibration to the deflection of the beam. Nouniform

strain field generated by beam bending is applied along the FBG and makes it chirped. A resistance strain gauge has been used for the comparison purpose and good agreement has been achieved. The power detection method reduces the cost and complexity of the sensor system. The proposed FBG vibration sensor is a promising candidate for practical vibration measurement.

5. Acknowledgements

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