Cantilever based FBG vibration transducer with sensitization structure*

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We report a fiber Bragg grating (FBG) vibration transducer based on an equal strength cantilever with enhanced sensitivity design. The sensitivity of the transducer is improved by a buffer layer of polyimide which increases the effective distance between the FBG and the neutral axis of the cantilever. The thickness of the polyimide layer is further optimized by finite element analysis (FEA). Vibration test results demonstrate that the sensitivity is enhanced by about 3.34 times than the conventional design, from the original 10.2 pm/g to 44.3 pm/g, which is consistent with the FEA. It is also shown experimentally that the sensitivity enhancement does not degrade the fundamental vibration characteristics of the cantilever, especially the resonant frequency.

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Fiber Bragg grating (FBG) sensors have drawn much attention in the last decade as they possess several advantages, such as immunity to electromagnetic and optical power fluctuations, as well as remote sensing and multiplexing capabilities[1,2].

Vibration monitoring is an important subject in industrial and civil engineering. Researches on fiber optical accelerometer have been conducted for several years[3-5]. Cantilever based structures are commonly used in FBG vibration sensors for the simple structure and stable performance[6-9]. However, cantilever structure has a deficiency that the resonant frequency and sensitivity severely restrict each other[10]. Thus, different structure designs for sensitivity enhancement have been reported. Teng Li[11] proposed a differential FBG accelerometer consisting of one main beam and two tiny beams with a resonance frequency of 250 Hz which is three times of that of the conventional cantilever-mass arrangement, so a sensitivity of 53 pm/g is achieved. A hypersensitive structure based on a bow beam has also been reported with a resonance frequency of 59.9 Hz and a high sensitivity of 458.1 pm/g[12]. However, these designs involve complex alterations of the conventional cantilever structure, and lose the characteristics and advantages of the classical cantilever beam.

The surface strain due to a bending beam is zero at the neutral axis, and enhances linearly away from the neutral axis. With this concept, a backing patch is used to increase the distance between the neutral axis of a constant-section beam and the FBG, and the sensitivity has been enhanced by twice without affecting the resonance frequency[13]. However, the constant-section beam used in the design would produce non-uniform strain distribution which caused a chirp FBG, and the thickness of backing patch has not been optimized. In this paper, an optimized sensitivity enhancement method is investigated based on an equal strength cantilever. A buffer layer of polyimide is also used to increase the distance between the FBG and the neutral axis of the equal strength cantilever. The thickness of polyimide layer is optimized by finite element analysis (FEA) and the experimental investigations. It is shown experimentally that the sensitivity is enhanced obviously without affecting the resonant frequency.

The configuration of the enhanced sensitivity design is illustrated in Fig.1(a). The prototype mainly includes an equal strength cantilever with a mass, a polyimide buffer layer and a single mode optical fiber with one FBG. The basic principle of operation is that the bending strain transfers to the polyimide buffer layer, then to the FBG attached on the surface of the polyimide layer, which results in a wavelength shift proportional to the vibration

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acceleration. The polyimide has excellent physical performance[14], so it is chosen as the buffer material. Both the polyimide layer and the FBG are fixed by a commercial epoxy.

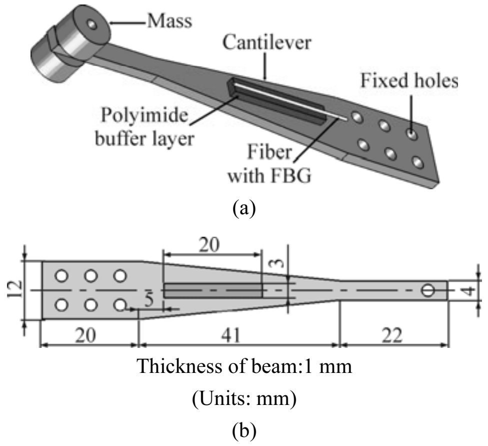


Fig.1 (a) Configuration and (b) key physical dimensions of the enhanced sensitivity structure

The strain detected by the FBG on the surface of polyimide with respect to the strain on the surface of the cantilever is expressed as[13]

$$\varepsilon_{\mathrm{FBG}} = \frac{0.5h + h_{\mathrm{P}}}{0.5h}\varepsilon_{\mathrm{C}}\ , \tag{1}$$

where $\varepsilon_{\mathrm{FBG}}$ is the strain detected by FBG, ε_{C} is the strain at the surface of cantilever, h is the thickness of the cantilever, and h_{P} is the thickness of polyimide layer. It should be emphasized that the FBG placed on the surface of the polyimide layer with thickness of h_{P} can produce a higher strain value compared with the strain on the surface of cantilever, and this assumption only holds if the Young's modulus of the additional layer is much less than that of the cantilever material[13]. The Young's modulus of the polyimide layer we used here is 2.55 GPa, which is much less than that of the stainless steel cantilever (210 GPa).

In order to obtain the maximum strain produced by the cantilever under the same vibration acceleration, we investigate an optimum matching thickness of polyimide buffer layer using FEA. The key physical dimensions of the composite cantilever are shown in Fig.1(b). The material of the cantilever is 201 stainless steel with Young's modulus of E_{C} =210 GPa and Poisson's ratio of μ_1=0.29. The Young's modulus of the polyimide is E_{P} =2.55 GPa, and its Poisson's ratio is μ_2=0.34. The mass fixed on the free end of the cantilever is made of copper, and its weight is 4.2 g. An axial force of 1 N is applied at the cylinder mass, which serves as the inertia force produced by vibration acceleration (here the inertia force applied on the cantilever itself is ignored). The variation trends of the strain on the polyimide surface detected by the FBG are analyzed under different thicknesses of polyimide buffer layer. The thickness is changed from 0 mm to 4.5 mm with a step of 0.3 mm. The structure modal analysis is also conducted under different thicknesses of polyimide. The simulated equivalent strain distribution and the first-order vibration model of the composite cantilever analyzed by FEA with the thickness of 0.6 mm are shown in Fig.2(a) and (b), respectively.

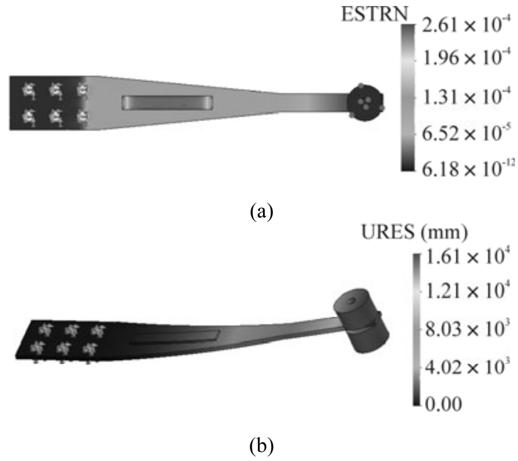


Fig.2 (a) Equivalent strain distribution and (b) the first-order vibration model by FEA

The variation trends of the strain on the polyimide surface and the frequency of the first-order vibration under different layer thicknesses are demonstrated in Fig.3. Notably, the maximum strain (498$\mu\varepsilon$) appears at the thickness of 2.7 mm, which is about 4.51 times of the strain value (110.5$\mu\varepsilon$) of the original cantilever without buffer layer. Thus, the optimum matching thickness of the polyimide buffer layer is 2.7 mm. The variation trend of frequency also demonstrates a modest increase from 100 Hz to 111.7 Hz, which implies that the additional layer does not degrade the resonant frequency.

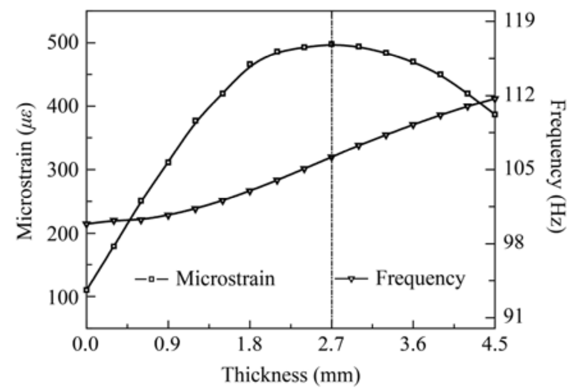
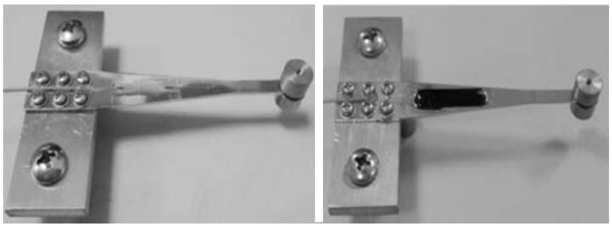


Fig.3 Trends of strain and frequency under different thicknesses of polyimide buffer layer

A series of vibration tests are carried out to investigate the response and sensitivity characteristics of the conventional directly attached FBG and the polyimide layer attached FBG. For comparing the performance of the conventional design and the enhanced sensitivity design, the same cantilever is fabricated in conventional vibration transducer and the transducer with enhanced sensitivity structure, respectively. An FBG with the center reflection wavelength of 1545.13 nm is directly attached on the surface of cantilever, and undergoes a series of vibration tests. Then we remove the directly attached FBG and fabricate a polyimide buffer layer with a thickness of 2.7 mm on the cantilever. Another FBG with the center reflection wavelength of 1545.10 nm is mounted on the polyimide layer, and the transducer with enhanced sensitivity undergoes the same vibration tests. Photographs of the directly attached transducer and the polyimide layer attached transducer are shown in Fig.4.



(a) (b)

Fig.4 Photographs of (a) directly attached transducer and (b) polyimide layer attached transducer

The setup of vibration test is shown in Fig.5. The test system contains a current driven shaker (B&K 4808), a shake driver (B&K 2719) and a standard piezoelectric accelerometer (B&K 4371). Wavelength shifts of FBG are recorded by a homemade FBG interrogator with acquisition frequency of 4000 Hz, accuracy of 1 pm and resolution of 0.1 pm.

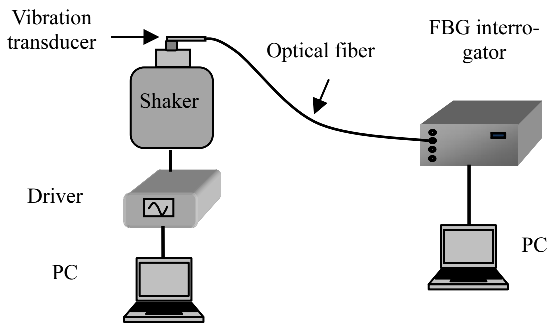
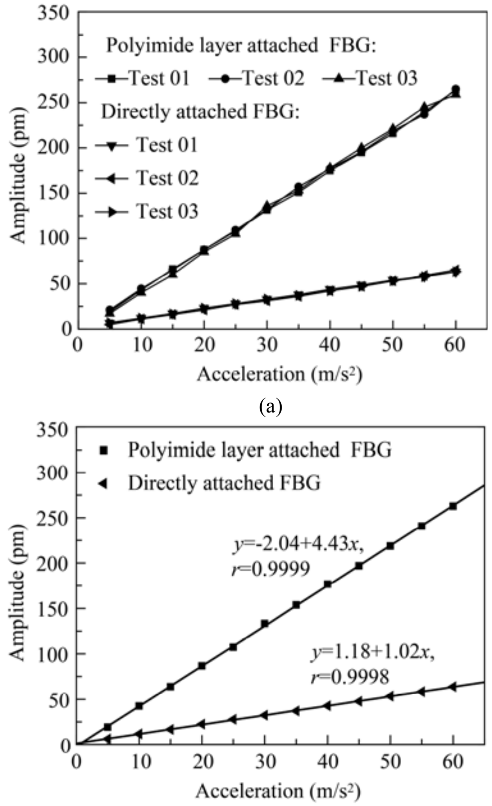


Fig.5 Experiment setup of the vibration tests

The sensitivity characteristics are investigated. During this test period, the vibration acceleration of a sinusoidal signal is raised from 5 m/s^2 to 60 m/s^2, whereas the vibration frequency is kept at 30 Hz. The test is repeated three times. The amplitude response and the fitting function of average values are demonstrated in Fig.6. The sensitivity of the directly attached transducer is observed to be 10.2 pm/g (g=10 m/s^2) with a linearity of 0.9998, and the repeatability error is 3.33% for three independent tests. The polyimide layer attached transducer has a sensitivity of 44.3 pm/g, linearity of 0.9999 and a repeatability error of 2.91%. The sensitivity of the polyimide layer attached transducer is enhanced by about 3.34 times than that of the conventional design, which is basically consistent with FEA result.

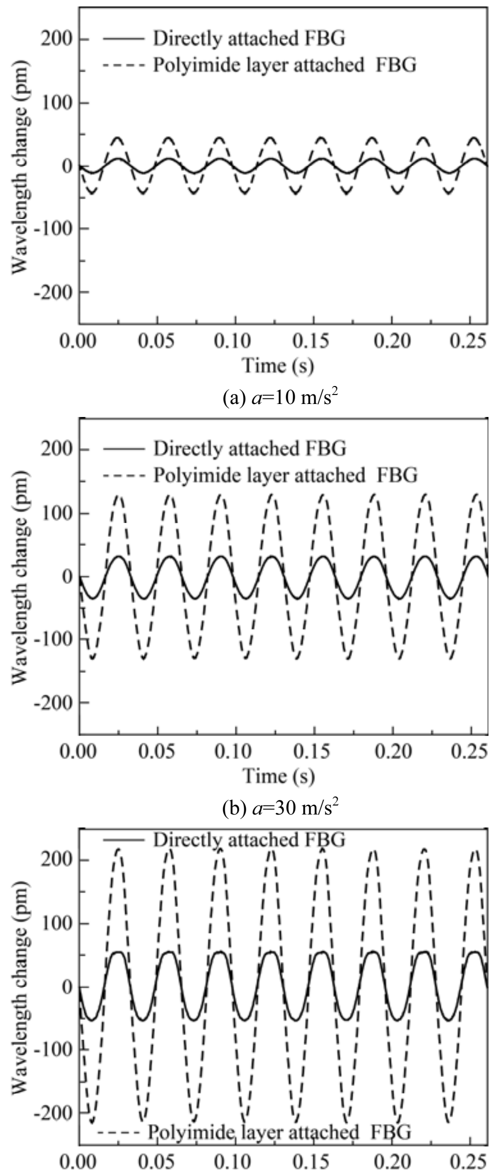


(b)

Fig.6 (a) Amplitude responses in three tests and (b) linear fitting lines of the average test data for directly attached transducer and polyimide layer attached transducer

The comparison of time responses of the two type transducers is plotted in Fig.7. Under the excitation frequency of 30 Hz, the waveforms of different amplitudes at acceleration from 10 m/s^2 to 50 m/s^2 are observed, which demonstrates a spectacular sensitivity enhancement.

The amplitude-frequency characteristic of a vibration transducer contains a large number of important parameters, including the resonant frequency of the sensor. The amplitude-frequency characteristics of the two type transducers are investigated through excitation with a frequency band from 10 Hz to 200 Hz, whereas the input acceleration is kept at 10 m/s^2. Fig.8 shows the amplitude-frequency response curves of the two type transducers, which indicates that the resonant frequencies of the directly attached transducer and polyimide layer attached transducer are 105 Hz and 115 Hz, respectively. The modest increase of resonant frequency from 105 Hz to 115 Hz is in accord with the results of FEA, which also demonstrates that an additional layer does not degrade the resonant frequency.



(a) a=10 m/s^2

(b) a=30 m/s^2

(c) a=50 m/s^2

Fig.7 Comparison of time responses of the two type transducers

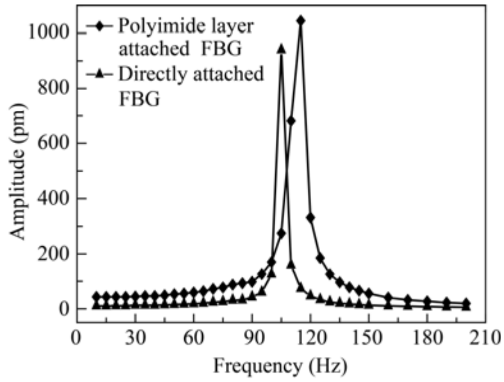


Fig.8 Amplitude-frequency curves of two type transducers

An optimized method is presented to enhance the sensitivity for a cantilever based FBG vibration transducer. The optimum matching thickness of the polyimide buffer layer is investigated by FEA. Comparison tests are conducted in respect of the sensitivity characteristic and the amplitude-frequency characteristic. The experiment results demonstrate that the sensitivity is enhanced by about 3.34 times than that of the conventional design, which is basically consistent with FEA. The additional polyimide buffer layer does not affect the fundamental vibration characteristics of linearity and repeatability, especially the resonant frequency. The paper contributes an effective way for high sensitivity FBG vibration transducer design.

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