Welding-packaged accelerometer based on metal-coated FBG

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A fiber Bragg grating-based accelerometer with a fully metalized package is presented. Magnetron sputtering and electroplating techneques are successively adopted to metalize bare SiO_2 fiber with a single Bragg grating. Laser welding techneque is adopted to fix the metal-coated fiber on the sensor component to obtain a fully metallized package without adhesives. Vibration test results demonstrate that the accelerometer has a flat frequency response over a 1-kHz bandwidth, with a resonance frequency of 3.6 kHz, wide linear measurement range of up to 8 g, and sensitivity of 1.7 pm/g .

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Fiber Bragg grating (FBG) sensors have drawn much attention in the last decade because of certain advantageous features, such as immunity to electromagnetic and optical power fluctuations, as well as remote sensing and multiplexing capabilities[1,2]. Packaging and fixing of optical fibers are some of the key problems in engineering applications because the optical fiber material itself is fragile. Currently, the typical methods used for such applications include polymer encapsulation and adhesive immobilization, both of which easily result in insensitivity, aging, and creep problems during long-term use[3]. Metal-coated FBG possesses many advantages, including enhanced sensitivity, high resistance to moisture attack, stability at high temperatures and welding access[4−6]. At present, metalized fiber research focuses primarily on the manufacturing process and on the temperature and strain characteristics[7,8]. Studies on vibration transducers are rarely reported.

Vibration monitoring is an important subject in industrial and civil engineering. Research on fiber optical accelerometer has been conducted for several years. As one of the most widely used fiber sensors, the FBG has been proven to be very effective. FBG-based vibration accelerometers are the topic of numerous studies and discussions, and various performances in terms of sensitivity, frequency response, and signal-to-noise ratio have been achieved[9−13].

Combining metal FBG and laser welding technology, this letter proposes a vibration accelerometer with a fully metallized package. Magnetron sputtering and electroplating technologies have been used for optic fiber copper coating. The metal-coated fiber with FBG is fixed on the mass and foundation by laser welding. The metallized fiber is used as an elastic element that improves the elastic coefficient, thereby effectively avoiding stretching of the naked grating.

The FBG accelerometer configuration and the actual image are shown in Fig. 1. The prototype mainly includes a metallized optical fiber with FBG, two end covers, a mass, and the package base. The metallized optical fiber is used as a spring element, and the FBG output undergoes a wavelength shift caused by the inertial force of the mass along the horizontal vibration direction. The resonant frequency and sensitivity can be tuned by the addition of mass.

The steps for metal-coated FBG preparation are as follows: firstly, a Cr (chromium) film (approximately 20 nm) is coated on a clean, bare single-model optic fiber by magnetron sputtering to achieve good adhesion toward the SiO_2 optic fiber[14]; secondly, an Ag (argentum) film (approximately 40 nm) is sputtered on the surface of the Cr film for excellent electrical conductivity; thirdly, a Cu (cuprum) film is electroplated onto the surface of the sputtered Ag film to increase the metalized layer thickness, such that the material (cuprum, H62) is in accordance with the sensor mass and end cover requirements for a strong laser spot welding result. After 3 h of electroplating, a metalized optical fiber with a diameter of 0.3 mm can be obtained. The

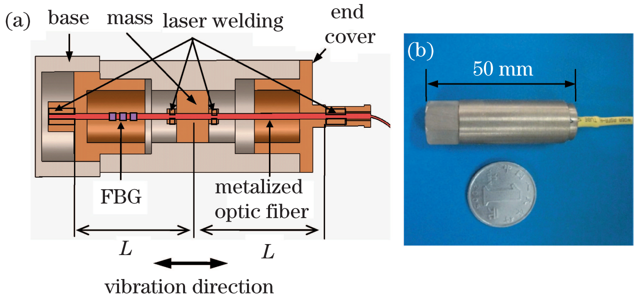


Fig. 1. (a) Configuration and (b) actual image of the FBG accelerometer.

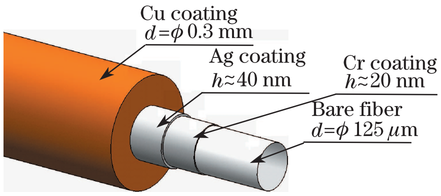


Fig. 2. Configuration of the metal-coated optic fiber.

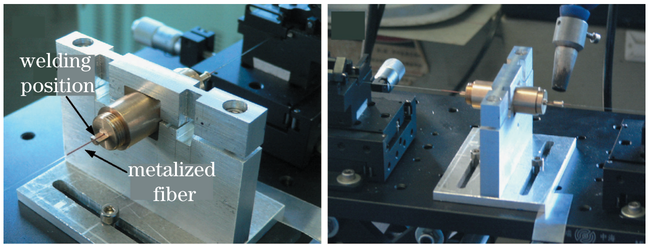


Fig. 3. Actual laser welding images.

sputtering system is specially designed for optical fiber coating, equipped with DC and RF sputtering sources. A 3-inch Cr (or Ag) target is installed on the DC and RF sources, and the distance between the FBG samples and the target is about 150 mm. The sputtering pressure of Ar is 0.5 Pa and the deposition power for the Cr (or Ag) target is 100 W, which correspond to a deposition rate of 0.14 nm/s. The plating solution composition is as follows: 175 g/L $CuSO_4{\cdot}5H_2O$, 55 g/L H_2SO_4 (98%), and 0.1 g/L NaCl, with a pH of 2.5 and a current of 10 mA.

The metal-coated optic fiber configuration is shown in Fig. 2. The metal coat is initially fixed to the mass by laser spot welding, followed by the two covers after an axial pretension force is exerted on the metalized fiber. The axial pretension force causes a wavelength shift of 1 nm. Both the mass and the two covers are made of cuprum (H62). Figure 3 shows the laser welding conditions. An accelerometer with a fully metallized package is created after the covers are welded to the sensor base. The wavelength–strain relationship of FBG can be expressed as[2]

$$\Delta\lambda = (1 - p_{\mathrm{e}})\varepsilon\lambda, \tag{1}$$

where $\Delta\lambda$ is the wavelength drift, p_{e} is the elasto-optical coefficient, ε is the axis strain, and λ is the wavelength of the Bragg grating.

The relationship between strain and acceleration in an elastic system[2] is

$$a = \frac{F}{m} = \frac{2ES}{m} \cdot \varepsilon, \tag{2}$$

where F is the resultant force on the mass, S is the metalized optical fiber in the cross-sectional area, m is the mass quality, and $E = (E_{\mathrm{f}}V_{\mathrm{f}} + E_{\mathrm{c}}V_{\mathrm{c}})/V$ is Young's modulus of the composite[15] composed of optic fiber and copper. E_{f} and E_{c} stand for the Young's modulus of optic fiber and cuprum, respectively, whereas V_{f} and V_{c} stand for the volume of optic fiber and cuprum, respectively. Cr and Ag coatings are ignored because the films are too thin. V is the volume of the composite. From Eqs. (1) and (2), the relationship between acceleration and FBG wavelength shift can be deduced as

$$\frac{\Delta\lambda}{\lambda} = \frac{m(1 - p_{\mathrm{e}})}{2ES} \cdot a. \tag{3}$$

From Eq.(2), the elastic coefficient of the metalized optical fiber can be written as

$$F = 2ES \cdot \varepsilon = 2ES\frac{\Delta L}{L} = \left(\frac{2ES}{L}\right) \cdot \Delta L = k \cdot \Delta L,$$

$$k = \frac{2ES}{L}. \tag{4}$$

The metalized optical fiber is divided into two parts by the mass, and L represents the length of each segment. Therefore, the resonant frequency of the accelerometer is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{2ES}{mL}}. \tag{5}$$

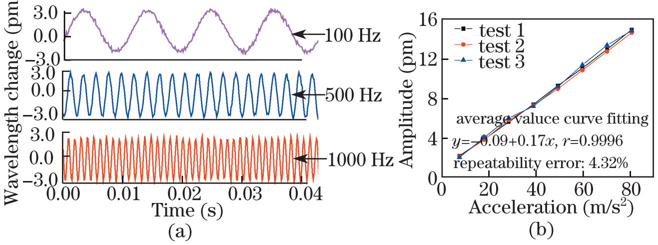
The parameters of this prototype are as follows: E_{f} = 72 GPa; E_{c} = 110 GPa; m = 4.8 g; L = 20 mm; and metalized fiber diameter d = 0.3 mm. The theoretical resonant frequency f can then be calculated to be 3 853 Hz.

The "B&K 4808" vibration test system and the standard "B&K 4371" piezoelectric accelerometer are used to measure the time and linearity response of the accelerometer. Wavelength shifts of FBG are recorded by a high-speed homemade FBG interrogator (acquisition frequency: 8 000 Hz, accuracy: 1 pm, resolution: 0.1 pm).

The time response of the accelerometer excited by a sinusoidal signal is plotted in Fig. 4(a). Under an acceleration of 1.5 g (in units of g=10 m/s^2), satisfactory response waveforms at the excitation frequency range of 100 to 1 000 Hz are observed, which demonstrates excellent acceleration measurement capability.

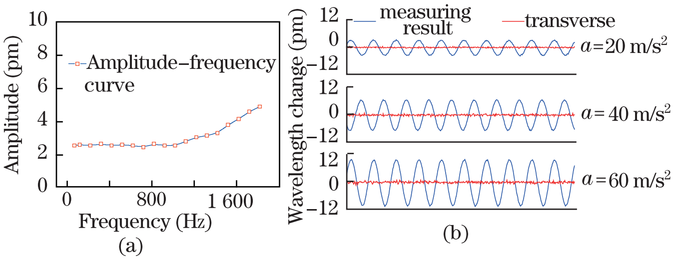
During the sensitivity test period, the vibration acceleration is raised from 1 to 8 g, whereas the vibration frequency is kept constant at 200 Hz. The test is repeated thrice. Linearity response values and average value fitting function are demonstrated in Fig. 4(b). From the fitted curve, the sensitivity of the accelerometer is observed to be 1.7 pm/g with a linearity of 0.9996. The repeatability error for three independent tests is 4.32%. The resolution of our FBG interrogator is 0.1 pm, which supports the accelerometer measurement resolution of 0.1/ (1.7 pm/g) = 0.059 g.

The flat frequency response region is an important accelerometer parameter. The flat region is investigated through excitation with a frequency band from 50 to



(a) (b)

Fig. 4. (Color online) (a) Time response under different vibration frequencies and (b) amplitude response linearities.



(a) (b)

Fig. 5. (Color online) (a) Amplitude–frequency characteristics and (b) cross-axis disturbance resistance.

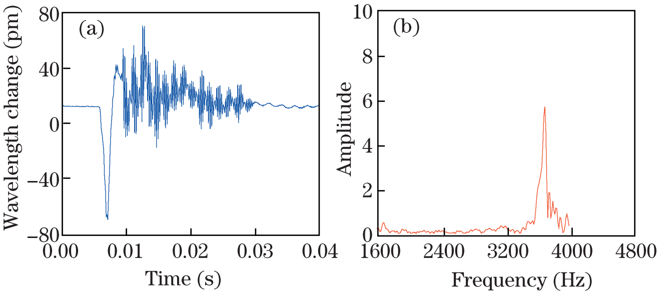


Fig. 6. Free shock response. (a) Time waveform signal and (b) spectrum.

1 800 Hz, whereas the input acceleration is kept constant at 1.5 g. Figure 5(a) shows the amplitude-frequency response curve of the accelerometer, from which a flat response from 50 to 1 000 Hz can be seen. As a one-dimensional measurement accelerometer, anti-interference at the transverse direction is inevitable in real-world applications. An input signal of 200 Hz with excitation accelerations of 2, 4, and 6 g is exerted on the accelerometer in both the measurement and transverse directions. Responses in the measurement and transverse directions are shown in Fig. 5(b), demonstrating that the prototype has a good anti-interference capacity.

To identify the natural frequency of the sensor, a shock test is performed. Figure 6(a) shows the time domain response of the accelerometer when a free shock force is applied. Through FFT transformation, the frequency response of a self-excited vibration is shown in Fig. 6(b). Notably, the resonant frequency of the accelerometer is about 3 600 Hz, which is basically consistent with the theoretical resonant frequency of 3 853 Hz.

In conclusion, a vibration accelerometer with a fully metalized package based on metal-coated FBG is investigated. The new sensor is small in size, immune to electro-magnetic interference, and can surmount aging and creep problems arising from the adhesive. These properties make this sensor a promising candidate for long-term and harsh-environment monitoring. Detailed experimental results demonstrate that the sensor has a flat frequency response over a 1-kHz bandwidth, wide linear measurement range of up to 8 g, repeatability error of 4.32%, sensitivity of 1.7 pm/g, and measurement resolution of 0.059 g. However, the obtained sensitivity is not sufficiently high for the measurement of a small accelerometer. This aspect needs to be improved in further research. In addition, by adjusting sensor parameters, different frequency ranges can be obtained.

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