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A simple intensity modulation based fiber-optic accelerometer

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ABSTRACT

A fiber-optic accelerometer with simple structure and high performance based on intensity modulation is proposed. Using only a length of single mode fiber compressed by a cantilever, the intensity of reflected light is modulated by the vibration acceleration applied to it. The effects of the fiber location, the dimension parameters of the cantilever on frequency response and sensitivity are investigated. The experimental results demonstrate that the accelerometer has a flat frequency response over a 4700 Hz bandwidth and a sensitivity of 21.24 mV/g with a cantilever dimension of $30 \times 8 \times 1.6$ mm^3 and a distance of 5 mm between the fiber location and the suspended cantilever end; the coefficient of determination is better than 0.999. In addition, the effect of temperature and the stability of the sensing system are investigated.

1. Introduction

Compared with the conventional sensors, optical fiber sensor offers important advantages such as electromagnetic interference immunity, high sensitivity and multiplexing capabilities [1,2], so it has been used widely in many fields [3–7].

According to the principle of optical fiber accelerometers, there are four types of optical modulation, namely, wavelength modulation [8,9], phase modulation [7,10], polarization modulation [11] and intensity modulation [12,13], in which the intensity modulation based accelerometer is realized by micro-bend of fiber or micro-displacement of reflecting mirror. In the above accelerometers, however, the sensor structure and the demodulation system are usually complicated, which may lead to some problems in real application such as high cost, instability.

In this paper, a novel fiber-optic accelerometer with high performance based on intensity modulation is proposed. Unlike the intensity modulation based accelerometers in [12,13], a cantilever is used to compress a length of single mode fiber at the frequency of vibration acceleration, which makes the transmissivity of the compressed part of the fiber vary. Consequently, the intensity of the light propagated in the fiber is modulated by the vibration acceleration.

The optical part for intensity modulation in the proposed accelerometer is simply a length of single mode fiber and the demodulation system is only composed of a broad band source, a polarization controller, an optical fiber circulator and a photodetector, all of which are simple and cheap compared with the accelerometers using a Fabry-Perot cavity, a mirror or an interferometer. Due to the simple structure of accelerometer and demodulation system, the stability is improved by introducing less ambient interference.

This paper demonstrates the structure and operation principle of the accelerometer and conducts a series of experiments to investigate the effects of the fiber location and the dimension parameters of the cantilever on frequency response and sensitivity of the accelerometer. In addition, the stability, the linear characteristic and the influence of temperature are also tested.

2. Principle of operation

The designed accelerometer is presented in Fig. 1. A square steel plate with a dimension of $50 \times 50 \times 2$ mm^3 is used as a substrate. A steel beam with a dimension of $L \times W \times H$ mm^3, and with one end of which is pressed by a narrow steel plate, is fixed on the substrate. The other end of the beam is suspended, which constitutes a cantilever. The characters L, W and H are the length, width and thickness of the steel beam, which are marked in Fig. 1(a) except H. The material of the substrate, steel beam and steel plate is 304 stainless steel. A length of single mode fiber connected to a circulator is put perpendicularly to and under the cantilever as the sensor head, so the fiber is compressed between the steel beam and the substrate. To prevent sliding, the fiber is fixed on the substrate by plastic adhesive tape, the thickness of which is 0.06 mm. The distance from the fiber to the suspended end of the cantilever is d, and the fiber length near the far end and remained outside the cantilever is about 1 mm.

When the substrate is excited by vibration acceleration, the cantilever moves up and down, making the fiber compressed and

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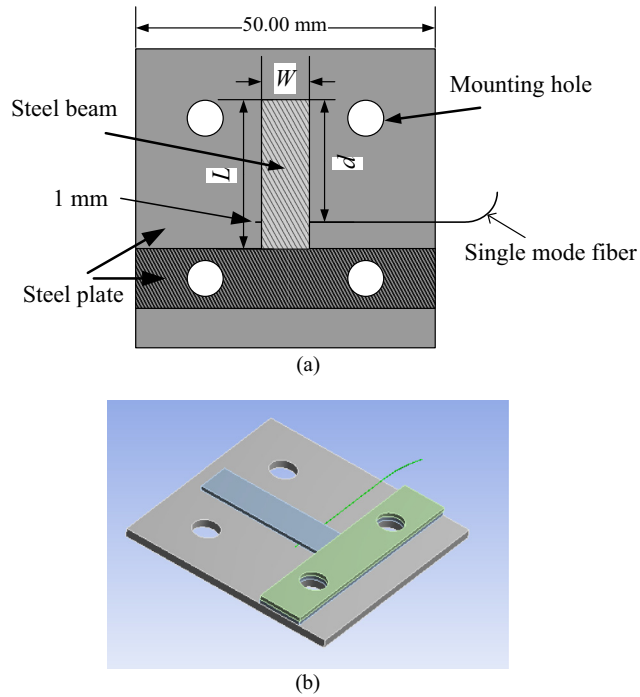

Fig. 1. Structure diagram of the accelerometer: (a) top view and (b) three-dimensional view.

recovered periodically. The fiber deformation makes a part of the guided mode transform into radiation mode and emit into the fiber cladding, as shown in Fig. 2. It can be seen that after modulated by vibration acceleration, the incident light is reflected by the fiber endface used as a mirror, and the reflected light is modulated again while passing through the deformation part of the fiber, so the relationship between the input and reflected output optical powers can be expressed as [14]

$$P_o = P_I[T_{trans}]^2 R \tag{1}$$

where P_o is the reflected power, P_I is the input power, T_{trans} is the transmissivity of the deformation part of the fiber, and R is the reflectivity of the fiber endface.

The power of incident light before the deformation part is defined as P_{I1} and the one after the deformation part is defined as P_{I2}, then T_{trans} can be defined as the ratio of P_{I2} and P_{I1}, and similarly as the ratio of P_{R2} and P_{R1}, which are the power of reflected light after and before the deformation part, respectively.

Since the optical fiber is made of silica and has high hardness, the deformation is very small and it can be considered that the change of the transmissivity is approximately linear with the vibration acceleration a applied to the accelerometer, and can be described as

$$\Delta T_{trans} \propto a \tag{2}$$

From Eqs. (1) and (2), it can be known that the change of P_o is also linear with the vibration acceleration in the first order approximation in a small range and can be given by

$$\Delta P_o \propto a \tag{3}$$

Thus, the vibration acceleration can be obtained by measuring the change of reflected optical power.

From the analysis above, the frequency of the reflected power change is consistent with the vibration acceleration frequency of the cantilever, so the frequency characteristics of the accelerometer are mainly determined by the cantilever. The first order natural resonant frequency of the cantilever can be calculated by [15]

$$\omega = \frac{3.515}{L^2}\sqrt{\frac{EJ}{\rho A}} \tag{4}$$

where L, E, J, ρ and A is the length, elasticity modulus, moment of inertia, density and sectional area of the cantilever, respectively.

The fiber under the cantilever plays a supporting role to the cantilever, so the natural frequency of the cantilever will vary when the fiber location changes [16].

When the length, width and thickness of cantilever changes, the mass of it m also changes. It is concluded in [14] that the displacement of the mass block at the free end of cantilever is directly proportional to the vibration acceleration, which can be described as

$$K \times f \approx m' \times a \tag{5}$$

where K is the stiffness of the cantilever, f is the displacement of the block and m' is the mass of the block. Although there is not a mass block at the free end of the cantilever proposed in this paper, the mass m of the cantilever can be viewed to be equivalent to the mass m' of the block. Thus, the Eq. (5) is still correct if m' is replaced with m.

Since the cantilever is made of elastic material, the change trend of displacement at other points of the cantilever should be in agreement with the free end. A larger change of the displacement leads to more change of the reflected optical power, therefore, the length, width and thickness of the cantilever will influence the accelerometer sensitivity to a large extent.

When the substrate is stimulated by vibration, the micro-bend will be generated, thereby leading to the microbend of the fiber attached to the substrate. However, the substrate is thick enough to ensure that the microbend is tiny, so the microbend induced intensity modulation is also tiny compared with the intensity modulation induced by fiber deformation. Thus, the microbend induced intensity modulation can be ignored in the analysis.

3. Experiment and discussion

3.1. Experiment setup

The experiment setup for performance test is shown in Fig. 3. The accelerometer is fixed on the vibration table through four mounting holes and a piezoelectric (PZT) vibration accelerometer is glued on the substrate by No. 502 glue as a reference. The light

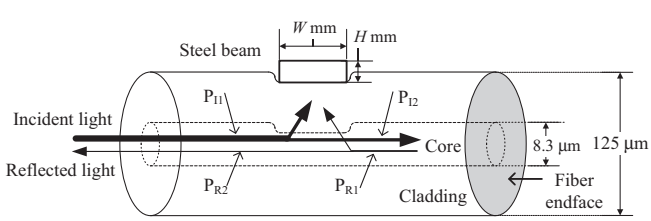

Fig. 2. Schematic diagram of transformation of guided mode into radiation mode.

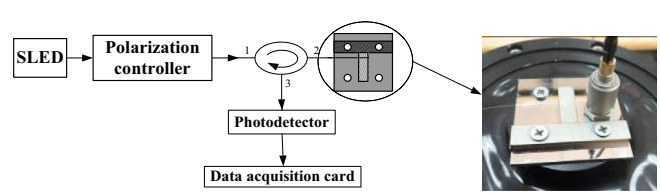

Fig. 3. Experiment setup.