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Sensitivity enhancement of optical fiber vibration sensor through encapsulation of acoustic Helmholtz resonator

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ABSTRACT

Optical fiber sensors should be encapsulated to prevent the possible damage in practical applications. Moreover, the encapsulation should be optimized to increase the sensitivity of the sensor as much as possible. Herein three different Helmholtz resonators are designed to encapsulate the singlemode-multimode-singlemode (SMS) fiber vibration sensor. Finite element analyses exhibit the acoustic pressure distributions in the resonators. The SMS fiber structures are fixed in the resonators with different schemes. Experiments demonstrate that the encapsulations increase the sensitivity of the sensors, which are determined by the fixing schemes, the acoustic pressure distributions, and the structures of the resonators. The combined resonator with two coaxially attached cavities renders the sensor a response range from 20 to 1000 Hz, which possesses a higher sensitivity and wider frequency response range than the sensor with a single cavity of resonator. The sensitivity of the encapsulated sensor with the combined resonator is 2.11 times of the sensitivity of the un-encapsulated sensor at 120 Hz. The SMS sensor encapsulated by the combined resonator exhibits a higher sensitivity than a commercial microphone, which indicates a favorable practicability of the Helmholtz resonator to the encapsulation of various kinds of fiber vibration sensors.

1. Introduction

Optical fiber possesses the merits of low loss of signal in the long distance transmission, high stability, anti-electromagnetic interference, anti-chemical corrosion, and good adaptation for integrations in many circumstances such as communication, industry, civil engineering, and military affairs. Due to these merits, the constructions of novel and practical fiber sensors are important works for the scientific and industrial communities, which are always pursued by researchers. Recently, fiber vibration sensor attracts increasing attentions in the field of acoustic vibration sensing due to its high sensitivity and wide frequency response [1]. Specific tasks in the research of fiber vibration sensor include the seeking of sensitive and effective sensing structures, and the encapsulation of the fiber sensor to prevent the possible damages in practical applications. Note that the encapsulation of the fiber sensor should increase the sensitivity of the sensor system as much as possible. Up to now, the optical fiber sensing structures that are applied to perform the acoustic vibration sensing include the fiber Bragg grating [2], the Fabry-Perot interferometer [3], the Mach-Zehnder interferometer [4], the tapered fiber structure [5,6], the singlemode-multimode-singlemode (SMS) fiber structure [7] and so on.

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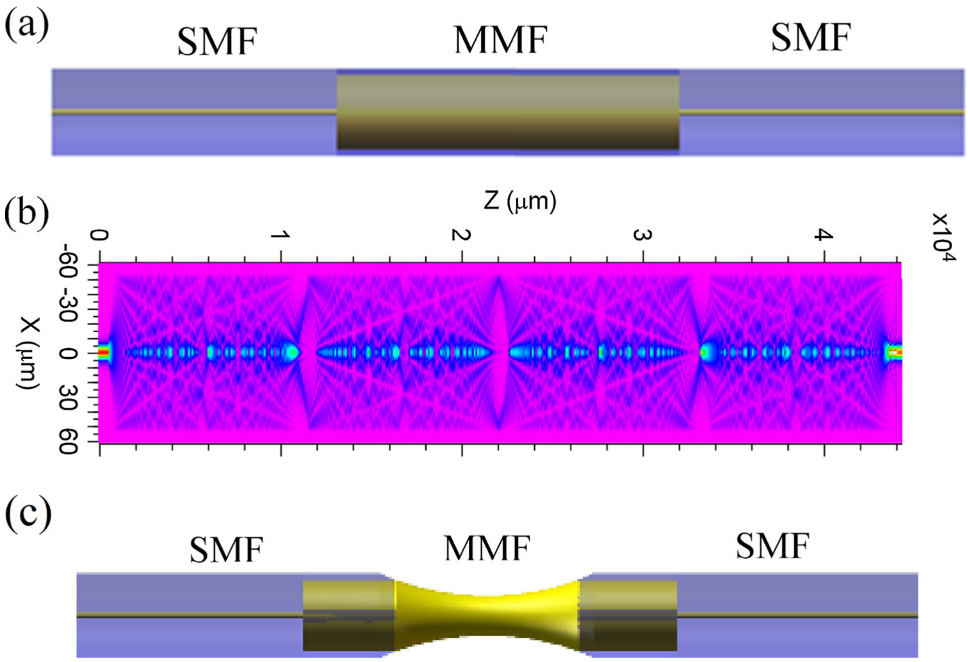

Fig. 1. (a) The schematic diagram of the SMS fiber. (b) The simulation of beam propagation in the SMS fiber, (c) The schematic diagram of the SMS fiber after the acid etch.

For the encapsulation of the fiber vibration sensor, there are some relevant works. S. Foster and co-workers packed a fiber vibration sensor into a capillary tube, which constructed a hydrophone that possessed a response range from 30 to 7000 Hz [8]. F.-X. Launay and co-workers packed a fiber vibration sensor into a tube to construct a hydrophone that possessed a response range from several to 8000 Hz, which exhibited an acoustic pressure sensitivity of 105 dB·Hz/Pa [9]. B. Tan and J. Huang proposed an encapsulation based on a Helmholtz resonator, the encapsulated sensor responded from 20 to 800 Hz with an acoustic pressure sensitivity of -131 dB·Hz/Pa [10]. J. Wang et al. proposed an encapsulation based on the fiber Bragg grating vibration sensor that responded from 5 to 100 Hz with an acceleration sensitivity of 450 pm/g [11]. Among these encapsulation structures, the acoustic Helmholtz resonator is an efficient structure and is promising in the field of acoustic vibration sensing. It is significant to explore these applications. On the other hand, in recent years, the SMS fiber sensor attracts interests for its high sensitivity [12–15]. The SMS fiber structure is constructed by connecting a multimode fiber (MMF) with a singlemode fiber (SMF) on one end and connecting another SMF on the other end. Special attentions should be paid to design and fabricate the SMS structure. For example, hydrofluoric acid etch is used to increase the sensitivity of the SMS sensor [16,17], however this process decreases the firmness of SMS structure. So the encapsulation of the SMS fiber structure is highly necessary to prevent the possible damage in practical applications. In this paper, three different Helmholtz resonators are produced to encapsulate the SMS structure and enhance the sensitivity of a SMS structure. The sensitivity of the SMS sensor with the optimized Helmholtz resonator increases 2.11 times comparing to that of the unencapsulated SMS sensor. The optimally encapsulated sensor possesses a higher sensitivity than that of a commercial microphone.

2. The SMS structure and Helmholtz resonators

The SMS structure consists of a MMF and two SMFs, as shown in Fig. 1(a). As the light in a SMF propagates into a MMF, a series of eigenmodes appear and interferences among these eigenmodes arouse. The intensity of the transmitting light in the MMF is periodic along the fiber, where the positions of the local maximum intensity are the self-imaging points (SIPs), as shown in Fig. 1(b). When the light in the MMF propagates to the output SMF, the maximum coupling efficiency can be obtained when the SMF and MMF connect at a SIP, which accordingly guarantees a high sensitivity of the SMS sensor. However, in the SMS fiber structure, when the MMF connects with the output SMF, there is always a certain deviation from the SIPs because an accurate connection is difficult to be achieved in practice, which greatly reduces the optical coupling efficiency and consequently leads to a dramatic decrease of the sensitivity. Recently, we proposed a method to avoid the accurate connection between the SMF and MMF, through which the SIP can be accurately adjusted to the connection of the MMF and the output SMF by hydrofluoric acid etch [16,17]. The acid etched taper on the MMF facilitates the vibration sensing and therefore increases the sensitivity, as shown in Fig.1(c). However the taper of the MMF may be damaged easily for its fragility. So in this work the acid etched SMS fiber sensor is encapsulated by the Helmholtz resonator.

An ideal Helmholtz resonator is theoretically equivalent to a vibration system [18,19]. When the acoustic wavelength is much longer than each dimension of the Helmholtz resonator, the air in cavity vibrates with the air near the holes, which forms a vibration system. Fig. 2 shows a typical structure of a Helmholtz resonator with four holes on its surface, the resonance frequency of the