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Research Progress of Fiber Grating Vibration Sensor

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Abstract. With the rapid development of fiber grating sensing technology, vibration sensor based on fiber grating sensing technology has become a new research and development direction. This paper focuses on the latest research progress of vibration sensors based on different structural principles of fiber gratings at home and abroad. The future development of fiber grating vibration sensor is prospected, and the future development of fiber grating vibration sensor is also discussed.

1 INTRODUCTION

Vibration sensors in the aerospace, marine engineering, earthquake, oil, bridges, machinery, military and other fields has been widely used [1]. In recent years, fiber optic sensor technology based on fiber optic sensor with its anti-electromagnetic interference, small size, light weight, wide dynamic range, high precision, can work in harsh environments have been the rapid development of the advantages [2]. In the past few decades, fiber optic vibration sensor has been a lot of research and reports, according to the parameters of light modulation can be divided into four categories: light intensity modulation [3-12], optical phase modulation [13-25] And optical wavelength modulation [26-40] vibration sensor, this paper mainly discusses the status of these three sensors.

2 LIGHT INTENSITY MODULATION TYPE FIBER VIBRATION SENSOR

The mechanism of light intensity modulation is: vibration acts on the fiber (contact or non-contact), so that the optical transmission of optical signal intensity changes, by monitoring the optical signal strength changes to achieve the vibration measurement. There are many types of light intensity modulation type vibration sensors, which can be divided into external modulation type [3-10] (modulation area outside fiber) and internal modulation type [11-12] (modulation area Within the fiber). External modulation type can be divided into reflective and transmission type; internal modulation type can be divided into micro-bend modulation and absorption modulation.

2.1 Reflective external modulation type fiber vibration sensor

Reflective external modulation optical fiber vibration sensor, with the principle of simple, flexible design, low cost, etc., so the research of such sensors has been a lot of research and reports [3-4]. Its working principle As shown in Figure 1.1, the input fiber will light emitted from the light source to the surface of the vibration target, and then by the output fiber to receive back from the vibration target light and transmitted to the photodetector, photodetector received light intensity With the measured target surface and the distance between the optical fiber changes. In 2007, S.Binu et al. Proposed the vibration of the shaking table by fixing the two mirrors by fixing the two plastic optical fibers together. The light source used is a single wavelength laser with a central wavelength of 660 nm, and the sensor The system can detect the frequency range is 75-275Hz [3]. The main feature of the sensor system is the low cost, but the laser output light intensity fluctuations and shaking table surface reflectivity changes will bring a greater error to the sensor.

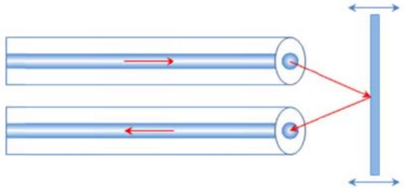


FIGURE 1. Schematic diagram of the reflective external light intensity modulated optic-fiber vibration sensor

FIGURE 2. Schematic diagram of the optic-fiber vibration sensor based on PC1Fs and LED

In 2009, G. Perrone and A. Vallan proposed as shown in Figure 2, the high-precision low-cost reflex non-contact strength modulation optical fiber vibration sensing system, the system is a non-coherent light source LED instead of the traditional laser, effectively reducing the cost of the sensor system, but also effectively increase the light output light intensity. At the same time, the optical fiber used in the experiment was a plastic optical fiber (POFs) with a core diameter of 0.98 mm made of Poly-Methyl-Methacrylate (PMMA) material, and the conventional single-mode optical fiber (inner diameter of about 9μm) and Compared with the larger core, the larger core achieves a large numerical aperture (about 0.5), and more light can be transmitted into the fiber at the receiving end. The experimental results show that the multi-mode fiber (about 62.5μm) The principle of the fiber optic vibration sensor can detect the vibration frequency range of several Hz to tens of KHz [4].

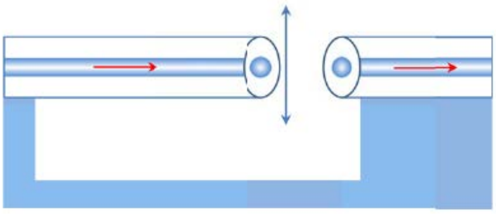


FIGURE 3. Schematic diagram of the transmission external light intensity modulated optic-fiber vibration sensor

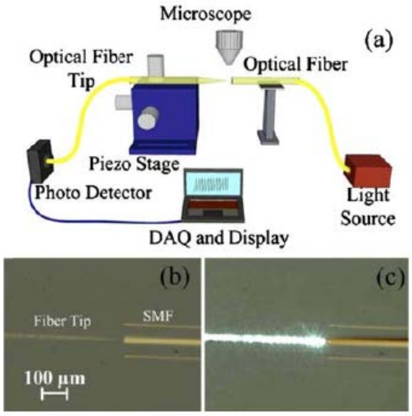


FIGURE 4. Schematic diagram of the transmission nanofiber vibration sensor

2.2 Transmission type external modulation type fiber vibration sensor

Light intensity modulation optical fiber vibration sensor can also use transmission modulation. Transparent external modulation is achieved by inserting a light shield between the input end of the input and output fibers or by changing the pitch or position [5] of the input and output fibers to achieve coupling between the input and output fibers Change the light intensity detected by the photodetector. In 1987, Rines [5] proposed a transmissive external modulating optical fiber vibration sensor based on the elasticity of single mode fiber (SMF). Its working principle is shown in Fig. 3, the input fiber is cantilever structure, Fixed, with the outside of the vibration input fiber due to inertia will occur vibration, input and output fiber coupling between the end of the external vibration will change, and thus changed the photon detector to detect the light intensity. Similar structures have also been reported by J. Kalenik et al. [6]. After Lopez-Higuera [7] and Doyle [8] and others on this basis, respectively, with two and four fiber to receive light intensity, its biggest advantage is to eliminate the impact of light intensity fluctuations, while the four fiber structure also Can achieve two-dimensional vibration measurement. In 2010, L. Su and S. R. Elliott of Cambridge University used the micro-nanofibers formed by the tapered cone to receive the outgoing light from the SMF, forming an optical fiber vibration sensor. As shown in Fig. 4, since the distribution of the light field emitted from the SMF is similar to the Gaussian distribution and the numerical aperture of the micro fiber for detecting the output light intensity is 50 nm, the displacement resolution thereof is very high and the detectable vibration amplitude For the 14.5 ± 0.5nm, the response frequency from 0Hz ~ 600Hz [9]. In 2013, the XY Bao team of the University of Ottawa in Canada [10] designed a transmissive vibration sensor with different etching rates of double-clad fiber. The structure of the vibration sensor is shown in Fig. 5, and the vibration frequency range is 5Hz ~ 10kHz The The advantages of the sensor is the vibration cantilever beam design and processing in the fiber inside, effectively reducing the size of the sensor to achieve the miniaturization of the sensor.

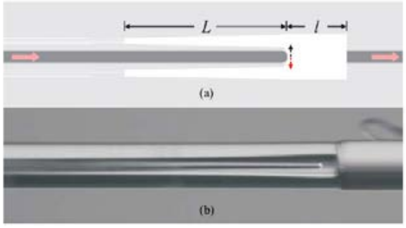


FIGURE 5. Schematic diagram of the in-fiber transmission microcantilever based vibration sensor

2.3 Micro - bend type internal fiber type vibration sensor

When the optical fiber under the action of external micro-bending occurs, it will cause the fiber in the different modes of energy from the new distribution, that part of the core module coupled to the cladding die, into a radiation mold or leakage mold, thereby increasing the loss of fiber, The so-called bending loss. Micro-bend fiber vibration sensor is a kind of early study of the vibration sensor [11-12], its working principle shown in Figure 6. Wherein the micro-bend deformer consists of two corrugated plates having a specific period, the period of which is determined by the propagation constant between the fiber modes. When the corrugated plate occurs perpendicular to the direction of the corrugated plate in the direction of vibration, will change the fiber within the mode of energy coupling, and then achieve the optical fiber transmission intensity modulation. Micro-bend fiber optic sensors can use either multimode fiber or single-mode fiber. JW Berthold [11] has analyzed the micro-bending properties of gradient multimode fiber and stepped multimode fiber in 1995, And used to measure vibration, stress and temperature and other environmental parameters. In 2001, G. Murtaza et al. Analyzed the microbending properties of ordinary single-mode fiber analyzed by finite difference beam propagation method, and analyzed the loss characteristics of micro-bend fiber optic sensor [12].

FIGURE 6. Schematic diagram of the microbend internal light intensity modulated optic-fiber vibration sensor

2.4 Absorption type internal modulation type fiber vibration sensor

X-ray, gamma rays will stain the fiber material - the corresponding absorption loss will increase, the output light intensity of the fiber will be reduced, so you can adjust the distance between the fiber and the ray to achieve vibration measurement. As shown in Figure 7, when the fiber is located in the radiation source radiation different locations, the radiation length and intensity are different , Therefore, the absorption loss is different, transmitted to the photodetector on the light intensity is also different.

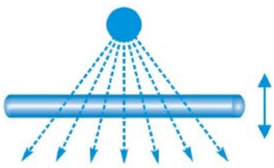


FIGURE 7. Schematic diagram of the absorbed internal light intensity modulated optic-fiber vibration sensor

The light intensity modulation type vibration sensor has the low precision. Therefore, high precision, high stability, miniaturization and appropriate compensation method is the focus of this type of sensor current and future research.

3 OPTICAL PHASE MODULATION TYPE FIBER VIBRATION SENSOR

The use of external vibration caused by changes in the optical fiber phase to detect the vibration of the sensor is called optical phase modulation type vibration sensor. Optical phase modulation type vibration sensor generally includes two parts: optical fiber interferometer and mechanical vibration response structure. Commonly used fiber interferometers generally include Michelson interferometer (MSI), Mach-Zehnder interferometer (MZI) and Fabry-Perot interferometer (FPI). Therefore, this paper will review the optical phase modulation type vibration sensor from the fiber MSI vibration sensor [13-17], the optical fiber MZI vibration sensor [18-19] and the optical fiber FPI vibration sensor [20-25].

3.1 Optical fiber MSI phase modulation type vibration sensor

The Michelson interferometer was designed by American scientist Michelson in 1881 and works for a beam of light that is divided into two beams of the same intensity, which are reflected and intervened after being reflected by different optical paths. Therefore, Michelson interferometer is a two-beam interferometer, Figure 8 is the fiber Michelson interferometer works schematic. The coherent light emitted by the laser is incident on two single-mode fibers (ie, the arms of the Michelson interferometer), one for the detection arm and the other for the reference arm. In the detection of vibration, generally by Michelson interferometer probe arm fiber fixed in a special vibration response structure, such as elastic cylinder [13], vibration beam [14], elastic film [15], when the outside vibration , The vibration response structure can transmit stress or strain to the detection arm, and then change the phase of the light in the probe arm fiber, by measuring the reflected light interference spectrum changes, you can detect the external vibration information. In 1995, RD Pechstedt et al. [13] proposed that by vibrating the upper and lower craters of the elastic cylinders, the intermediate design mass blocks, using the inertial forces of the mass blocks, respectively, to load the compressive and tensile stresses of the fiber Signal measurement, the sensor diagram shown in Figure 9. In 1999 D. L. Zhang et al. [14] fixed the probe arm of the Michelson interferometer on a mechanical vibration response structure, as shown in Fig. When the external vibration occurs, the relative movement between the substrate and the mass will produce a stress change with the external vibration on the detection arm, thus changing the interference intensity of the MSI, forming a fiber-based vibration sensor based on MSI, The frequency range is 5Hz ~ 500Hz. In 2003, Liu Yang team used 6 hollow cascading pillars to support a mass, forming a three-dimensional harmonic vibration sensor, the acceleration sensitivity of 15.7×10^3 rad/g[16]. In 2005, Tianjin University achieved a Michelson interferometric accelerometer based on a simple harmonic oscillator. The phase detection sensitivity was about 1.11×10^{-2} rad/(m/s^{-2})[17]. In 2011, GY Chen et al. [15] achieved a measurement of the vibration information by fixing the probe arm to a disk of a polymeric carbon material by applying a bending stress to the detection arm by bending stress during disc vibration. The structure is shown in Figure 11.

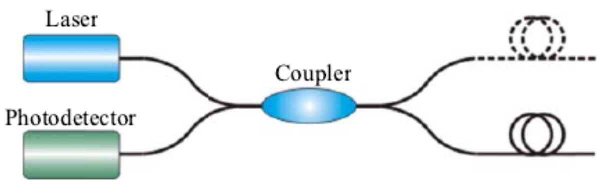


FIGURE 8. Schematic diagram of the optic-fiber Michelson interferometer

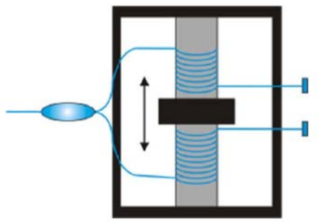


FIGURE 9. Optic-fiber MSI vibration sensor based on an elastic cylinder

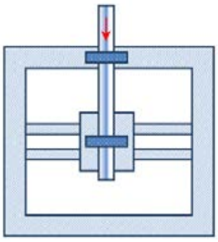


FIGURE 10. Optic-fiber MSI vibration sensor based on a mechanical structure

3.2 Optical fiber MZI phase modulation type vibration sensor

The Mach-Zehnder interferometer was independently proposed by the Austrian physicist Mach and the Swedish physicist Zendell in 1891, respectively. Fiber Mach-Zehnder interferometer and Michelson interferometer is similar, but also dual-beam interferometer, the difference is that MZI does not use the end of the reflection, but with the fiber coupler directly to the arms of the light coupling together interference, that is, Interferometer, the schematic diagram shown in Figure 12. The principle of the vibration sensor based on the optical fiber MZI is the same as that of the optical fiber MSI vibration sensor. The vibration response structure can transmit stress or strain to the detection arm when the vibration of the probe arm is fixed on the special vibration response structure. , And then change the phase of the light within the probe arm fiber, by measuring the interference spectrum of two transmitted light, with the external vibration changes, you can detect the external vibration [18-19]. In 2000, H. L. Rivera et al. [18] fixed the single-mode fiber on the variable-displacement column to form the MZI sensing arm, and the measured acceleration value can be obtained by demodulating the change of the optical phase signal in the fiber of the sensing arm. In 2005, Tsinghua University Zeng Nan et al. [19] proposed a 3-component fiber-optic acceleration sensor that could be used for reservoir monitoring by designing three single-component sensing units in a three-dimensional orthogonal direction. The sensor has good linearity, consistency and stability, the detection of vibration frequency range of 10Hz ~ 800Hz, which can detect the minimum acceleration value is 39.3 $\mu g/Hz^{1/2}$.

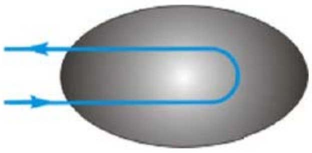


FIGURE 11. Optic-fiber MSI vibration sensor based on an elastic disk

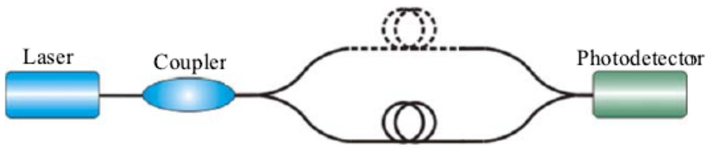


FIGURE 12. Schematic diagram of the optic-fiber Mach-Zehnder interferometer

3.3 Fiber FPI phase modulation type vibration sensor

The Fabry-Perot interferometer was designed by the French scientist Fabry and Perot in 1899. The resonator is composed of two precisely parallel reflecting surfaces. The incident light enters the resonant cavity and occurs on the two reflecting surfaces of the resonator Multiple reflections, the adjacent two reflected light phase difference is the same, all the reflected light into the detection system, the occurrence of multi-beam interference. The structure of the FPI is shown in Fig. 13. According to the composition of the reflecting surface, the optical fiber FPI can be divided into two types, one is the FPI [21] formed by the surface of the vibration target as the second reflecting surface; the other is the FPI composed of the dual fiber end face, the optical fiber FPI of this type The sensor is generally designed to fix external vibrations by measuring the deformation or stress of the mechanical vibration response structure by fixing the FPI to some mechanical vibration response structures [22-24]. Such mechanical vibration response structures mainly include cantilever beams [23] Rectangular plate, elastic rope [22], diaphragm [25] and so on. In 1998, Norbert et al. [20] designed a sensor based on a mass-spring system with a reflector on the end of the mass, which formed an enamel cavity on the end of the fiber. When the vibration signal was applied to the sensor, the mass The inertia leads to changes in the length of the cavity, and the vibration information can be measured by measuring the amount of change in the cavity. In 2005, TK Gangopadhyay et al. [21] proposed an optical fiber external cavity type FPI vibration sensor with a schematic representation of the light from the self-focusing lens as shown in Fig. 14, which is incident on the end face of the self-focusing lens and the elastic mirror FPI, when the external vibration occurs, the elastic mirror vibration will change the cavity length of FPI, by checking its phase change, to achieve the detection of external vibration. In 2010, a task group [23] formed FPI by welding a PCF in the middle of two SMFs. The structure is shown in Fig. 15 (b), and then the whole FPI is fixed at the root of the isosceles cantilever cantilever, By measuring the external vibration caused by the deformation of the triangular beam to achieve the measurement of external vibration. In order to realize the miniaturization of the fiber optic vibration sensor, Zhang Qiang [24] uses the micro-fiber processing technology to integrate the vibrating beam and the mass block on the ordinary single-mode fiber, and proposes a full-fiber-type simple support based on hollow fiber and microstructure fiber Beam type low frequency vibration sensor. The sensor has the advantages of small size, high sensitivity and temperature incompatibility.

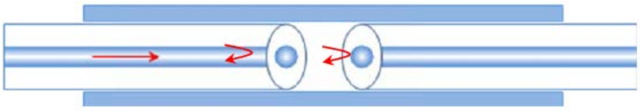


FIGURE 13. Schematic diagram of the optic-fiber FP interferoaneter

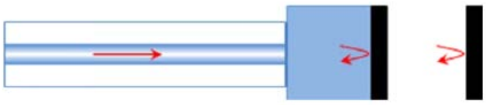


FIGURE 14. Optic-fiber extrinsic FPI vibration sensor

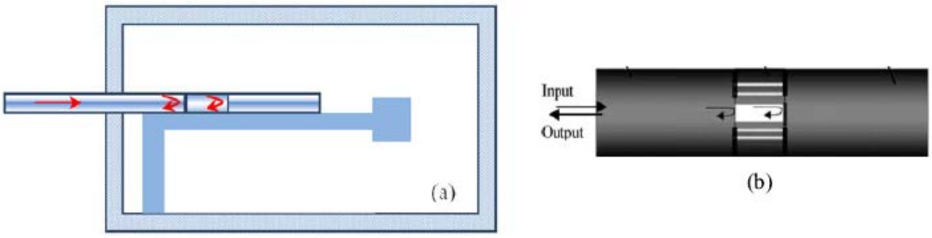


FIGURE 15. (a) Schematic diagram of Optic-fiber cantilever FPI vibration sensor, (b) FP interferometer based on PCF

4 OPTICAL WAVELENGTH MODULATION OPTICAL FIBER VIBRATION SENSOR

Optical wavelength modulation type vibration sensor refers to when the external vibration acts on the optical fiber, causing the wavelength of the optical fiber to produce drift, by measuring the optical wavelength drift to detect the external vibration of the sensor is the optical wavelength modulation type vibration sensor. In the optical wavelength modulation type vibration sensor to fiber grating vibration sensor research and application of the most popular, therefore, mainly discusses the fiber grating vibration sensor research status. According to the type of grating, can be divided into fiber Bragg grating (FBG) and long-period fiber grating (LPFG) type.

Since the K. O. Hill team [26] proposed a large number of FBG-based studies in fiber-based Bragg gratings in 1978 [27]. Commonly used FBG cycle is generally below 1μm, and LPFG refers to the cycle of about 100μm fiber grating. The LPFG is a transmissive grating whose function is to couple the light of a particular wavelength propagating in the fiber into the cladding. LPFG is widely used in optical fiber communication, such as mode converter [28] filter [29] and gain flat element [30]. Since long-period fiber grating is sensitive to changes in external environmental factors, it is also used in a large number of applications In the field of sensing [31].

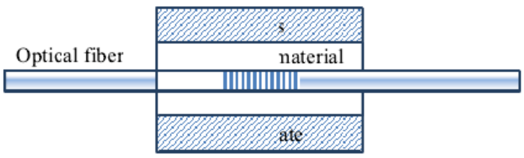


FIGURE 16. Compliant-material based FBG vibration sensbr

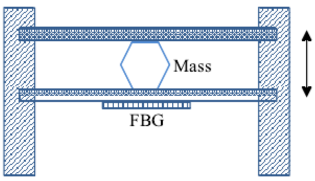


FIGURE 17. Simply-supported-beam based FBG vibration sensor

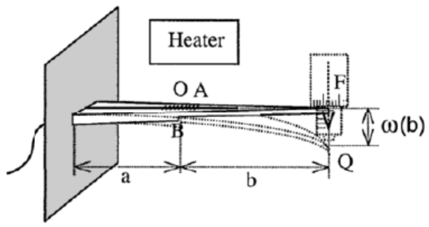
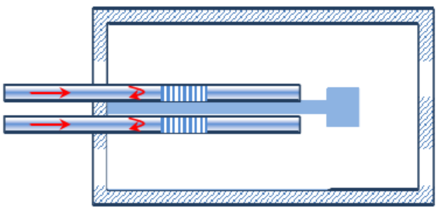


FIGURE 18. FBG vibration sensor based on an isosceles triangle beam with different thinknesses

The grating-based wavelength-modulated vibration sensor, which has been reported now, measures the vibrations of the outside by measuring the deformation of the mechanical vibration response structure caused by external vibrations by fixing the FBG or LPFG to a specific mechanical vibration response structure, The mechanical structures include cantilever beams [32,33], simply supported beams [34], plates [35, 36], and the like. As early as 1996, T. A. Berkoff et al. [37] achieved a measure of vibration by measuring the central wavelength drift of an FBG by implanting an FBG into the elastomer material, as shown in Fig. In 1998, the MD Todd team [34] formed a vibrating response structure of a double simply supported beam mass by machining a mass in the middle of the two simple beams as shown in Figure 17. Professor Jin Wei's team of the Hong Kong Polytechnic University [33] and the Y. Yu team [32] have reported vibration sensors based on FBG and isosceles cantilever beams, and temperature and displacement based on FBG and unequal-thickness cantilever beams as shown in Figure 18.



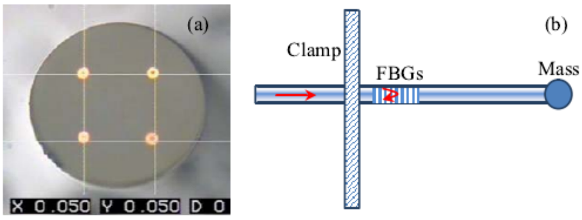


FIGURE 19. Cantilever based FBG vibration sensor **FIGURE 20.** Four-cores-fiber based FBGs vibration sensor

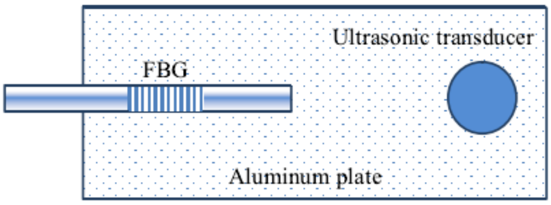


FIGURE 21. Aluminum-plate based FBG vibration sensor

In 2001, K. S. Chiang et al. [35] of the City University of Hong Kong, by means of FBGs on both sides of the mechanical vibrating beam, achieved a vibration measurement that was not affected by external temperature changes. The structural diagram is shown in Fig. 2008 A. Fender team [38] proposed by the special fiber (four core fiber) in the same position of the different core to write three different center wavelength FBG, to achieve a vibration direction can detect the vibration sensor, its structural diagram such as Figure 20 shows a detectable frequency range of 30-3000 Hz. In 2008, G. Msalza et al. [39] placed a Bragg grating on a vibrating arm to achieve a two-dimensional measurement of acceleration using light intensity demodulation. 2010 H. Tsuda et al. [36] placed the FBG in a toroidal laser with a schematic representation of the structure shown in Fig. And paste in a rectangular aluminum plate, aluminum plate for receiving vibration signals, by measuring the output of the ring laser light intensity measurement. From 2008 to 2013, Guo et al. [40] proposed a variety of vibration and tilt sensors based on tilted FBG, which realized the identification of directional vibration by using biased optical fibers and tapered optical fibers. In order to eliminate the inconvenience caused by the mechanical vibration response structure and realize the miniaturization of the fiber optic vibration sensor, Zhang Qiang [41] proposed two micro-structured miniature low-frequency vibration sensors based on microstructure fiber Bragg gratings, both of which have miniature And the temperature is not sensitive and so on.

5 CONCLUDING REMARKS

With the development of fiber grating technology, the research on the vibration sensor of fiber grating is heating up at home and abroad, and the vibration sensors with different structures, different applications and new sensing materials have been researched and developed. Fiber grating vibration sensor technology has received more attention. With the development of aerospace, structural engineering and large-scale mechanical fault diagnosis and testing industries, vibration sensors will usher in greater development, fiber grating vibration sensor research in the ascendant.

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