Fiber Bragg grating based displacement sensors: state of the art and trends

Wenlong Liu, Yongxing Guo, Li Xiong and Yi Kuang
Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education,
Wuhan University of Science and Technology, Wuhan, China and Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, China

Abstract

Purpose – The purpose of this paper is to present the latest sensing structure designs and principles of information detection of fiber Bragg grating (FBG) displacement sensors. Research advance and the future work in this field have been described, with the background that displacement and deformation measurements are universal and crucial for structural health monitoring.

Design/methodology/approach – This paper analyzes and summarizes the existing FBG displacement sensing technologies from two aspects principle of information detection (wavelength detection, spectral bandwidth detection, light intensity detection, among others) and principle of the sensing elastomer structure design (cantilever beam type, spring type, elastic ring type and other composite structures).

Findings – The current research on developing FBG displacement sensors is mainly focused on the sensing method, the construction and design of the elastic structure and the design of new information detection method. The authors hypothesize that the following research trends will be strengthened in future: temperature compensation technology for FBG displacement sensors based on wavelength detection; a study of more diverse elastic structures; and fiber gratings manufactured with special fibers will greatly improve the performance of sensors.

Originality/value – The latest sensing structure designs and principles of information detection of FBG displacement sensors have been proposed, which could provide important reference for research group.

Keywords Fiber Bragg grating (FBG), Structure design, Displacement sensor, Information detection

Paper type Literature review

1. Introduction

Measurement of displacement, deformation, perturbation and other physical parameters are crucial for structural health monitoring (SHM) (Housner *et al.*, 1997). With the emergence of optical fiber sensing technologies, their unique advantages such as signal anti-interference, remote transmission, easy integration and high sensitivity have rapidly advanced the field of SHM. Various types of optical fiber sensors have become the focus of research in both academia and engineering. Besides, they have been gradually applied in SHM including civil engineering (Guo *et al.*, 2015; Yazdizadeh *et al.*, 2017), mechanical equipment (Javdani *et al.*, 2016), robot (Guo *et al.*, 2016) and aerospace industry (Panopoulou *et al.*, 2011; Ramly *et al.*, 2012; Chen *et al.*, 2013). Fiber Bragg grating (FBG) sensing technology is one of the main components of optical fiber sensing. FBG sensors have many advantages such as wavelength coding with accurate measurement points, and multiple FBGs can be arrayed into a single fiber. What is more, the wavelength signal is unaffected by the fluctuations of the light intensity. In recent years, with the rapid development of FBG displacement sensors, domestic and foreign scholars have conducted extensive researches to advance the sensing principle, improve the elastic body design and the information detection methods. This paper briefly introduces the basic principle of FBG displacement sensors and summarizes the state of the art in the research of sensing principle and information detection methods. This paper also presents the potential development in this field.

2. Principle and classification of fiber Bragg grating displacement sensors

The physical parameters measured directly by the FBG sensor are axial strain and temperature. To measure the external displacement, an FBG sensor must convert the displacement information into the axial strain exerted on FBG. The basic schematic diagram of FBG displacement sensor is shown in Figure 1. The external displacement exerts on the sensing structure, which will cause deformation-induced strain. Furthermore, the strain is also exerted on the FBG, which causes the changes of these information of wavelength, bandwidth, light intensity and so on. After finishing calibration experiment, the external displacement could be obtained by detecting the changes of these information.

In this paper, according to the principle of information detection and elastomer structure design, the FBG

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displacement sensors have been summarized and classified. The classify diagram is shown in Figure 2.

3. Wavelength detecting fiber Bragg grating displacement sensors

The central wavelength of the FBG is sensitive to both axial strain and temperature. The FBG displacement sensor converts the external displacement information into a wavelength shift of the FBG. When a beam of broadband light is incident upon an FBG sensor, the axial strain and temperature variations can result in the Bragg wavelength shifts of gratings, which are used as the output signal of the FBG sensor. Using this information, the optical spectrum analyzer (OSA) inverts the external displacement information to detect the central wavelength shifts. The wavelength detecting FBG displacement sensors can be classified into different types based on their different structure designs. These sensors are listed as follows.

3.1 Fiber Bragg grating displacement sensors based on cantilever beam structures

FBG displacement sensors can have different types of elastic transition structures. Cantilever beam is a highly stable and simple structured classical elastic element widely used in FBG based sensors. In a cantilever beam with constant strength, the generated strain is distributed equally over the entire beam surface. The FBG is attached to the surface of the equal strength beam. When the free end of the beam is subjected to external displacement variation, the FBG will be subjected to a uniform strain, which avoids the chirp phenomenon in reflection spectrum caused by non-uniform strain on the FBG. A cantilever structure for the FBG displacement sensor was proposed (Guan *et al.*, 1999). As shown in Figure 3, in their proposal, the FBG is bonded to the surface of the cantilever beam. The beam converts the displacement of the measured object into a deflection of the beam, and then the deflection-induced strain is sensed by the FBG, which leads to the central wavelength shift of the grating. The wavelength shift of the FBG is linearly related to the displacement of the free end of the cantilever beam. Nevertheless, the design adopts an equal section cantilever beam rather than equal strength beam, which cannot avoid chirp phenomenon in reflection spectrum, and the sensitivity of the sensor is slightly lower. Furthermore, the strain and temperature cross-sensitivity problem influences the experimental result. Therefore, this structure cannot meet the high precision needs that the work requires any more.

In recent years, researchers have proposed and demonstrated a variety of principles to design displacement sensors based on cantilever beam structures. Zhang used a bilateral cantilever beam and a single FBG to achieve temperature-compensation and simultaneously measure temperature and displacement (Zhang *et al.*, 2001). However, the defect of the system is that it cannot avoid the chirp phenomenon in reflection spectrum, thereby possibly affecting the measurement accuracy of the central wavelength. Moreover, the practical application of this sensor is limited by small measuring ranges from 0 to 3.5 mm and poor durability. If this sensor device is optimized, it is expected to monitor deformation and stabilization in some

Figure 1 Basic schematic diagram of FBG displacement sensors

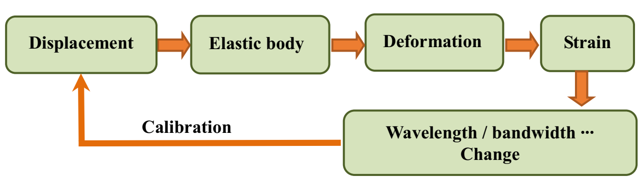


Figure 3 FBG displacement sensor with an equal section cantilever beam structure

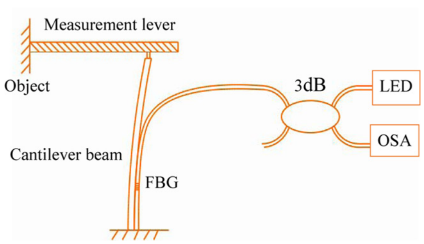
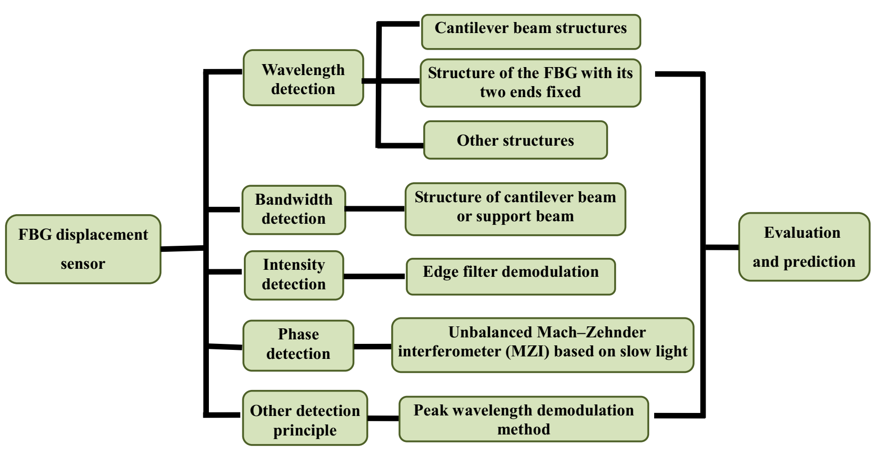


Figure 2 Classify diagram of FBG displacement sensors



building structure. An FBG sensor with simultaneous sensing of displacement and temperature was presented (Dong *et al.*, 2001). This sensor is mainly applied in the area of distributed embedded sensing in materials for creating smart structures. As shown in Figure 4, one part of the FBG (FBG1) was attached to the surface of the beam, and the other part (FBG2) was attached to the surface of substrate. FBG1 and FBG2 components responded differently to the temperature and displacement variations. By measuring the shifts in the two new Bragg wavelengths, the displacement and temperature could be measured simultaneously. Nevertheless, the structure also contained chirped-signal which affected the measurement accuracy. The proposed displacement sensor with sensitivity of 1270 pm/mm, resolution of 0.0787 mm and a measurement range of 0-10.5 mm. Although the problems of low sensitivity and cross-sensitivity have been solved, these displacement sensors are limited by small measuring ranges. Applications based on FBGs sensors in oil and gas industry, seismic investigation and oil exploration have become a popular research because of their attractive advantages. FBG displacement (or high-pressure) sensors based on equal strength cantilever structures were reported (Zhao *et al.*, 2002, 2004). Figure 5 shows the schematic diagram of the differential FBG displacement sensor, where two FBGs are bonded to the upper and lower surfaces of the beam. Based on the principle of differential measurements and the special designed structure, the Bragg wavelengths of the upper and lower surfaces shift toward longer and shorter wavelength directions can be observed, respectively. The difference in the two shifted Bragg wavelengths is used as the output signal of the sensor. The displacement sensitivity is approximately 1750 pm/mm, and the estimated displacement measurement resolution can reach 0.0057 mm in case the wavelength shift measurement resolution is 0.01 nm. According to the proposed method and sensor's structure design, the problem of cross-sensitivity is solved and the resolution is improved. In addition, the sensor is compact and electrically passive and can safely work in corrosive or explosive environments, such as oil and gas industry, seismic investigation and oil exploration.

Figure 4 Schematic diagram of the cantilever-based FBG displacement sensor

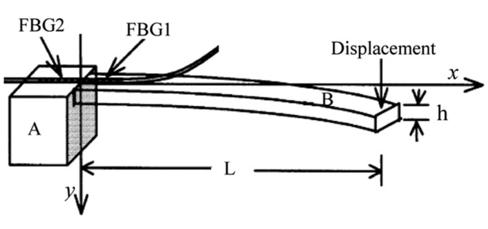
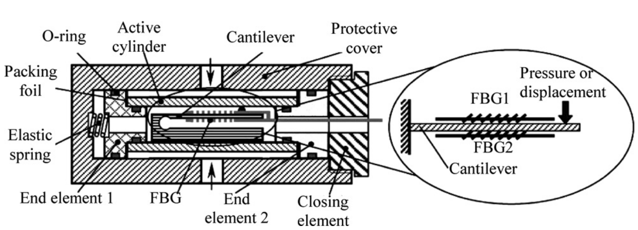


Figure 5 Schematic diagram of the differential FBG displacement sensor



Researchers have also reported the effect of combining a cantilever beam with other elastic elements. By leveraging the different properties of deformation of these elastic elements and the superposition of the beam deflections, a larger ranges of displacement measurement has been achieved by some researchers (Wang *et al.*, 2007; Tian *et al.*, 2016; Chen *et al.*, 2015; He *et al.*, 2010; Zhao *et al.*, 2015; Guo *et al.*, 2017; Cui *et al.*, 2011; Fu *et al.*, 2009). A composite sensing structure consisting of spring and equal section cantilever beam was proposed (Wang *et al.*, 2007). The other researchers replaced the constant section beam with an equal strength cantilever beam (Tian *et al.*, 2016). As shown in Figure 6, this design adopted the differential measurement method and an isosceles triangle cantilever structure can achieve temperature self-compensation. The range of the sensor is 0-70 mm, the sensitivity is 21.9 pm/mm, the degree of linear fitting is as high as 0.999, the repeatability error is 4.72 per cent FS and the hysteresis error is 2.70 per cent FS. The theoretical analysis and experimental results prove that this sensor can be well applied in long-term monitoring of the cracks or seam open degree in the water conservancy and hydropower engineering, industrial and civil buildings.

It should be noted that the long-term use of the sensor requires it to withstand frequent variations in external displacement. The changeability of the elasticity coefficient of force-transmitting medium (e.g., spring) will affect the magnitude of the force transmitted to FBGs or beam under the same displacement, thereby affecting the measurement accuracy in sensors. To solve this problem, some technologies were proposed. The authors connected a hydraulic telescopic cylinder to a cantilever beam in series (Chen *et al.*, 2015). As shown in Figure 7, the sensing element (FBG) is composed of a single mode fiber and a photosensitive fiber and provides two separate FBG wavelengths for temperature compensation. The two fibers have different responses to different external variations – the deformation responses caused by the displacements are different while the temperature responses are almost same. Therefore, the problem of cross-sensitivity has been solved, and the displacement can be obtained by measuring the difference of wavelength shifts between two

Figure 6 FBG displacement sensor combined with a spring and cantilever beam

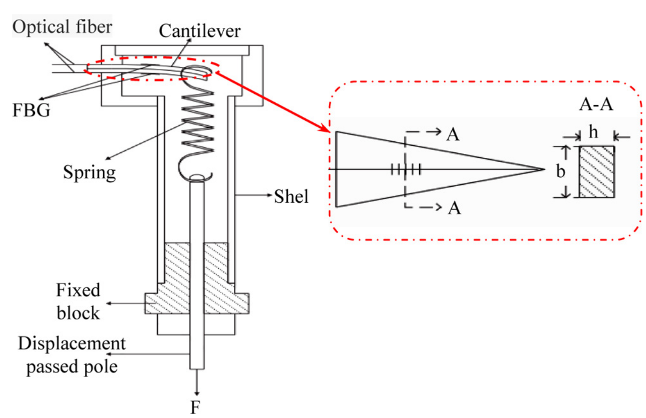
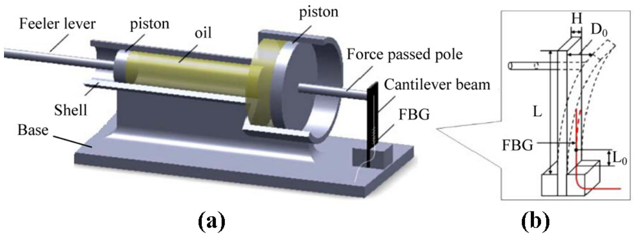
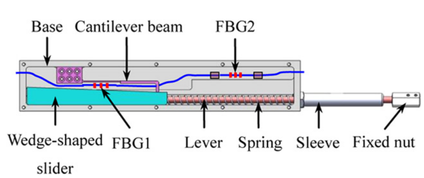


Figure 7 (a) Transducer based on hydramatic structure; (b) cantilever beam attached to the FBG



FBG wavelengths. This design improves the limitations accompanied with the changeability of the elasticity coefficient of force-transmitting medium such as springs, and it achieves a relatively lager measurement ranges up to 45 mm with a sensitivity of 36 pm/mm. The proposed sensor can be developed for real-time displacement monitoring in many industrial environments such as the mechanical shape or liquid level monitoring. However, it seems like to be complex and inconvenient for practical application due to the use of hydraumatic structure. Other structure designs have combined a wedge-shaped slider with the cantilever beam (Guo *et al.*, 2017; Cui *et al.*, 2011; Fu *et al.*, 2009). As demonstrated in Figure 8, the free end of the cantilever beam contacted with the inclined plane. When the slider moves under external displacement, it causes the cantilever beam to bend. This bending strain of the beam surface is sensed by the FBG to measure the displacement. Meanwhile, the range of measurement and sensitivity of the sensor can be adjusted by changing the inclination and length of the slider. The displacement sensitivity of the two sensors are 20.11 pm/mm in the range of 0-100 mm and 123 pm/mm in the range of 0-20 mm. The measurement accuracy of the two sensors is 0.0995 and 0.0081 mm, respectively. These excellent performances satisfy the requirements of high precision and long-term stability in SHM of machinery equipment and civil engineering. It is generally known that real-time of temperature compensation is always a difficult problem faced by FBG sensor research field. As shown in Figure 8(a), FBG1 and FBG2 are packaged differently, and the big difference of the temperature sensitivity coefficient is inevitable. According to the experimental results of temperature compensation characteristic, it can be seen that the response time of FBG2 lags behind that of FBG1. That is because FBG2 is a bare grating, and it only senses the temperature inside the sensor. However, FBG1 is attached to the elastic beam and is sensitive to the thermal strain on the beam during the temperature change. As a result, response time to temperature of FBG1 is faster than FBG2. Therefore, the compensation method is

Figure 8 Displacement sensor design with a wedge-shaped slider and a cantilever beam: (a) design of the single cantilever beam



applied to the measurement environment where the rate of temperature changes slightly.

3.2 Structure of a fiber Bragg grating with its two ends fixed

Directly designing an FBG as elastic element can help create a displacement sensor with high sensitivity. A displacement sensor for slope monitoring was designed (Zhang *et al.*, 2011). As shown in Figure 9, these two springs connected with two gratings in series, and the external displacement can be measured by the amount of stretching of the spring by the transfer device. In the same year, Mi and Nan (2011) proposed a non-contact magnetic coupling FBG displacement sensor depicted in Figure 10. The FBG is stretched directly as an elastic element. When the gap between the moving object and the magnetic coupling changes, the magnetic force also changes, resulting in an FBG axial strain. This causes its central wavelength to shift, and the displacement of the moving object can be obtained by measuring this shift. Experiments demonstrated the static and dynamic sensitivity are 823 pm/mm and 749 pm/mm in the range of ± 0.2 mm, respectively. In this design, the problem of cross-sensitivity can be solved well and has good dynamic frequency response characteristics in dynamic measuring process, but this sensor based on electromagnetic principle has some limitations. For instance, this sensor cannot work under uncharged, strong electromagnetic interference, flammable and explosive environment. Furthermore, the relation between of the FBG central wavelength shift and relatively displacement of measured object is nonlinear, and the problem of cross-sensitivity has not been solved in static property experiment. Therefore, the further work is focuses on temperature compensation method and further increase response frequency for measuring higher speed vibration displacement. Considering the importance of absolute

Figure 9 Structure of thread pulling FBG displacement sensor

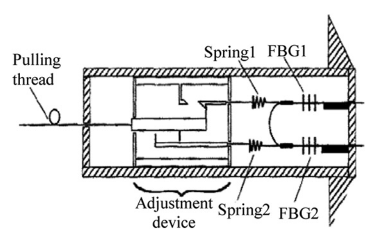
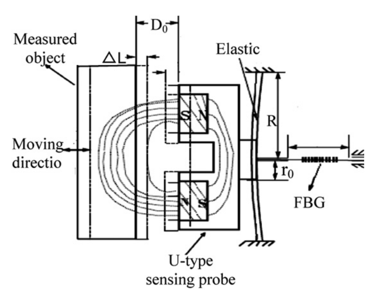


Figure 10 Structure of non-contacting magnetic coupling FBG displacement sensor



displacement monitoring and the limitation of normal displacement monitoring, a micro FBG displacement sensor with self-compensating for measuring the absolute displacement of rock mass was proposed (Jiang *et al.*, 2013). As illustrated in Figure 11, the FBG2 and the elastic body are performed in series, while the free FBG1 is used as a temperature-compensated grating. The proposed sensor can obtain a relatively higher sensitivity of 267 pm/mm with a linearity of 0.99. The experimental results show that the sensor can achieve temperature compensation and successfully reduce the influence of temperature changes on the results of the measurements. Based on the analysis of experimental results, it is proved that the sensor meets the demands of the experiment and has perfect practicability in the model experiment of undersea tunnel.

Compared with the above-mentioned FBG displacement sensors, Li *et al.* (2017a,2017b) proposed two sensors that can be used to measure the sub-micrometer displacement for SHM, which achieved the higher sensitivity and resolution. As far as one of them is concerned, the fiber is suspended with a pre-tension force, and its two ends are glued on the sensor frame, as shown in Figure 12. This slider and the T-shaped cantilever beam formed a conversion mechanism. As the change of the external displacement, the horizontal displacement can be converted into vertical movement exerted on the fiber midpoint. The external displacement can be obtained by the corresponding FBG central wavelength shift and the structural parameters of the conversion mechanism. This proposed design avoids the problems of chirped signal and low repeatability. In addition, it has an excellent sensitivity of 2086.27 pm/mm and a high resolution of 0.48 μm within a range of $1.0 \sim 2.0$ mm. However, this experimental results indicate that the relationship between the FBG central wavelength shift and displacement is nonlinear, which will result in inaccurate measurement results. Furthermore, FBG is directly stretched as elastic component, so the measurement range of displacement is relatively smaller. All these set limitations for the practical application of this kind of displacement sensors. Therefore, this sensor can be used for considerable applications in engineering fields for displacement and deformation detection, especially for micro systems, such as micro-scaled manufacturing, precise positioning and displacement measurement.

3.3 Other structures of fiber Bragg grating displacement sensors

There are other designed structures of FBG displacement sensors which have also been proposed by researchers in addition to the aforementioned types of sensor structures. As shown in Figure 13, Jiang *et al.* (2015) designed and fabricated an FBG displacement sensor with a variable measurement precision based on a helical bevel gear. In the diagram, the helical bevel gear is connected to the measured object and records the displacement. The free end of the beam generates the bending strain which is sensed by the FBG by recording the wavelength shift. In this case, the external displacement is obtained by measuring the wavelength shift of the FBG. Moreover, the measuring range of this sensor is from 0 to 153.2 mm, and the precision grade changes from 0.2 to 6.7 per cent. On analyzing the experiment data, it is confirmed that this sensor has excellent practical application, especially in large-scale engineering structure measurement.

To measure rail displacement of high speed railway, because of zero drift, and because the rail is used as return circuit of train power, and under the open-air meteorological conditions, traditional electrical sensor is difficult to realize long-term monitoring. Therefore, a displacement sensor with an FBG deformation ring was proposed (Li *et al.*, 2012). The displacement sensitivity is 27.53 pm/mm, and a displacement resolution of 0.1 mm within a range of 0-50 mm. As shown in Figure 14, two FBGs are fixed on this ring, and as the ring is deformed horizontally, the FBG A is stretched horizontally and the FBG B is compressed vertically. The external displacement

Figure 11 Schematic diagram of micro FBG displacement sensor

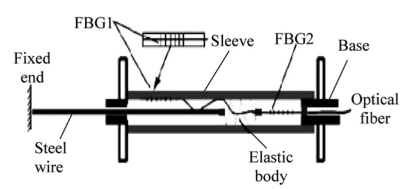


Figure 12 Schematic diagram of the FBG displacement sensor with a sub-micrometer resolution

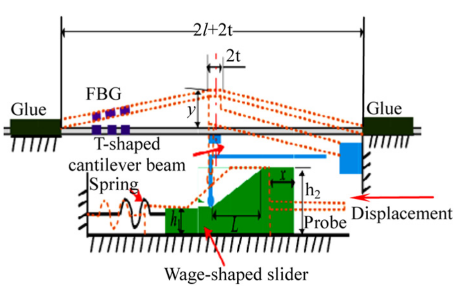
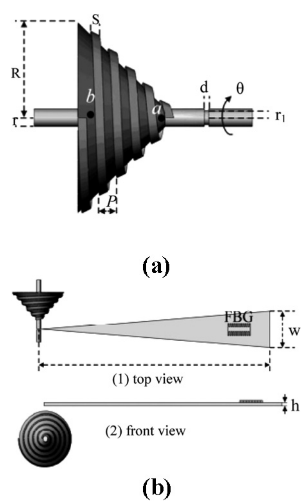
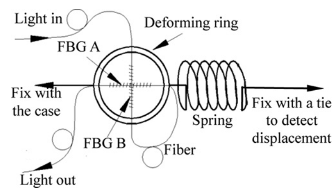


Figure 13 The schematic diagram of the displacement sensor based on helical bevel gears



Notes: (a) Design diagram; (b) theoretical calculation model

Figure 14 Structural schema of the FBG displacement sensing unit



can be obtained by measuring the difference of the wavelength shifts between these two gratings. Nevertheless, if the spring is used as the transmission medium of the measurands, the elasticity coefficient will be liable to change under the frequent working condition. So this will lead to the error of the test results. Li *et al.* (2015) designed, fabricated and tested an FBG sensor for long-ranges cryogenic displacement measurement. In this sensor setting, the FBG1 sensor is attached to one end of the spring, and its wavelength shifts with the changes of external displacement. Besides, the FBG2 hangs freely to compensate for the temperature variations. The sensor was proved to have excellent practical application at both room temperature and 77 K, a sensitivity of 14 pm/mm with 0.142 mm accuracy in a long-range up to 550 mm.

In general, these sensors of wavelength modulation are easily multiplexed and do not need complex demodulation schemes, but it suffers from the relatively lower resolution due to the use of OSA. Furthermore, compared with the use of cantilever beams with pasted FBG, the packaging method of pre-stretched and double-end can avoid chirped signal and obtain the relatively higher sensitivity. However, most of these sensors are usually limited by the small ranges of measurement.

To sum up this section, the main characteristics (i.e. application field, range of measurement, sensitivity, resolution and accuracy) of wavelength detecting FBG displacement sensors are reported in Table I.

4. Fiber Bragg grating displacement sensors for spectral bandwidth detection

It is generally known that many designed structures of FBG displacement sensors based on wavelength demodulation suffered from chirping failures due to the nonuniform strain distribution of the pasted FBG element. For these designs, the greater the non-uniform axial strain, the wider the bandwidth; thus, it is unsuitable for wavelength demodulation; however, the spectral bandwidth can be used for the measured target detection. As the bandwidth is unaffected by the temperature changes, which avoids the defect that it is necessary to set up a temperature-compensated grating for the wavelength modulation.

It is well-known that chirped fiber Bragg grating (CFBG) is usually used as filters (Han *et al.*, 2006) and dispersion compensator (Kim *et al.*, 2004) in optical communication field. More recently, researchers have proposed and reported many sensors based on CFBG which can eliminate the measurement errors caused by temperature variations. A method for measuring the displacement by using a CFBG based on a double triangular cantilever beam had been demonstrated (Zhang *et al.*, 2008). The bandwidth of the reflected spectrum of the CFBG is compressed by the forced deformation of the beam. Moreover, the temperature variation only results in the wavelength shift of the grating with few spectral bandwidth, which improves the cross-sensitivity effect.

Based on the FBG chirped effect and a specially designed cantilever beam, an FBG displacement sensor was proposed (Wei *et al.*, 2011). The displacement sensitivity is 480 pm/mm, the displacement measuring resolution is 0.2 mm and the displacement measuring range is 0-8.5 mm. In their research, a single FBG was available to the displacement and temperature simultaneously sensing. However, it is difficult to guarantee the FBG's midpoint coincide exactly with the zero strain layer of beam, which will result in the FBG reflected spectrum fluctuates; thus, it is difficult to precisely obtain reflected spectrum bandwidth variations. A similar structure was previously proposed (Dong *et al.*, 2005). As illustrated in Figure 15, in this design, it can be seen that only a single FBG is glued obliquely onto the lateral side of the specially designed cantilever beam. The bandwidth of the FBG varied linearly with the displacement of the free end of the beam and was inherently temperature insensitive. Displacement sensing was obtained by measuring the reflected optical power of the signal from the FBG. The relationship of reflection spectra and the displacement variations were plotted in Figure 16. The sensitivities of bandwidth-displacement and center wavelength-temperature are 356.4 pm/mm (range of 0-13 mm) and 37.9 mv/mm (range of 9.0 mm). As the effect of temperature-insensitive sensor, this configuration avoids the need for temperature compensation process. However, it brings application inconvenience due to the use of photo-detector and OSA simultaneously. Besides, there exists the defect that a photo-detector is needed for compensating the optical power fluctuation and inconvenient in multiplexing due to the use of the power demodulation method.

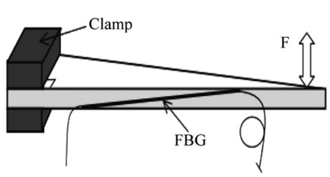
As shown in Figure 17(a), Shen and Zhong (2011) designed an FBG displacement sensor based on a double equal strength beam structure. A similar structure design (Zhong *et al.*, 2012) is displayed in Figure 17(b). In the diagram, an FBG is affixed into a V-shaped groove located on the lower surface of a double equal strength beam. The bandwidth and the optical power of the FBG vary linearly with the change in the displacement of the beam. Displacement measurement was achieved by measuring the bandwidth and the optical power of the reflection spectrum of the FBG. Compared with the sensor based on double-isosceles triangle structure cantilever beam, this temperature insensitive sensor uses the power demodulation method which can obtain relatively higher sensitivities of 250 pm/mm and 3.7 mW/mm (Figure 18).

An FBG displacement sensor based on a double-arched-beam had been proposed (Zhao *et al.*, 2008, 2011). As shown in Figure 18, an FBG is attached to each of the positive and negative strain sections on the beam surface. As the displacement increases, the bandwidth of the reflected spectrum of the FBG becomes broader and broader. External displacement can be obtained by demodulating the spectral bandwidth of the FBG. Besides, the spectral bandwidth is temperature-insensitive; thus, the cross-sensitivity problem is improved. Tao presented a bandwidth-demodulated FBG displacement sensor based on a thin-wall ring with accuracy of ±0.04 mm, a high sensitivity of 567 pm/mm and a displacement range of 0-3.5 mm (Tao *et al.*, 2016). Besides, the

Table I Performances and SHM applications for FBG displacement sensors based on wavelength demodulation

Reference	Method of signal demodulation	Application field	Range (mm)	Sensitivity (pm/mm)	Resolution (μm)	Accuracy (μm)
Guan *et al.* (1999)	wavelength demodulation	General purpose	>20	320	/	120
Zhang *et al.* (2001)	wavelength demodulation	Building structure	$0 \sim 3.5$	317	630.9	/
Dong *et al.* (2001)	wavelength demodulation	Distributed embedded materials for creating smart structures	$0 \sim 10.5$	1270.6	78.7	/
Zhao *et al.* (2004)	wavelength demodulation	Oil and gas industry, seismic investigation and oil exploration	$0 \sim 0.8$	1750	5.7	/
Wang *et al.* (2007)	wavelength demodulation	Geotechnical engineering	$0 \sim 100$	39.43	50	/
Tian *et al.* (2016)	wavelength demodulation	Industrial and civil buildings, Hydraulic and Hydro-Power Engineering	$0 \sim 70$	21.9	/	/
Chen *et al.* (2015)	wavelength demodulation	Displacement monitoring in industrial environments	$0 \sim 45$	36	/	/
He *et al.* (2010)	wavelength demodulation	Civil engineering	$0 \sim 100$	~12.27	80	80
Guo *et al.* (2017)	wavelength demodulation	Machinery equipment and civil engineering	$0 \sim 100$	20.11	5	99.5
Cui *et al.* (2011)	wavelength demodulation	Civil engineering	$0 \sim 20$	123	8.1	8.1
Fu *et al.* (2009)	wavelength demodulation	Civil engineering	$0 \sim 100$	50	/	20
Zhang *et al.* (2011)	wavelength demodulation	Slope deformation monitoring	$0 \sim 200$	/	/	20
Mi and Nan (2011)	wavelength demodulation	Monitor axial or radial vibration of machines	$-0.2 \sim 0.2$	823 (Static) 749(Dynamic)	/	/
Jiang *et al.* (2013)	wavelength demodulation	Model experiment of undersea tunnel	$0 \sim 1.75$	267	/	3.7
Li *et al.* (2017a,2017b)	wavelength demodulation	Displacement and deformation detection for micro systems	$1.0 \sim 2.0$	2087.27	0.48	/
Li *et al.* (2017a,2017b)	wavelength demodulation	Mechanical engineering (e.g. large-size machine tools)	$0.7 \sim 1.4$ 1.4~2.0	340.5 490.1	2.94 2.04	/
Jiang *et al.* (2015)	wavelength demodulation	Large scale engineering structure	$0 \sim 153.2$	/	/	$0.2\% \sim 6.7\%$ (precision grade)
Li *et al.* (2012)	wavelength demodulation	High speed railway	$0 \sim 50$	27.531	100	/
Li *et al.* (2015)	wavelength demodulation	Cryogenic environment	$0 \sim 550$	14	35	142

Figure 15 Equal strength cantilever beam structure



designed structure installed with a long metal bar can be used as a long gauge strain sensor or a crack gauge in civil engineering. As depicted in Figure 19, the FBG was symmetrically attached at the zero-strain point on the inner surface of the ring. The external displacement was measured by demodulating the spectral bandwidth. Figure 20 depicts the relationship of the bandwidth of the FBG's reflection spectrum

Figure 16 Plot of the FBG reflection bandwidth variations versus different displacements

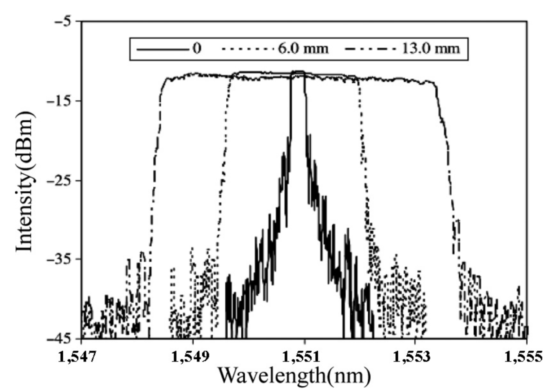
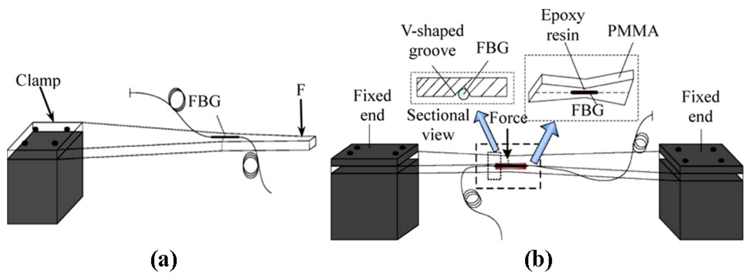


Figure 17 Schematic diagram of the double equal strength structure beam



Notes: (a) Double-isosceles triangle structure beam; (b) double-trapezoidal structure beam

Figure 18 Structure of the double-arched-beam based FBG displacement sensor

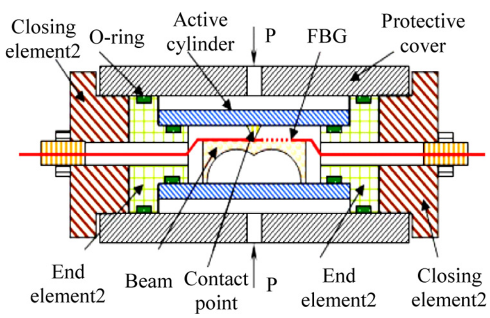
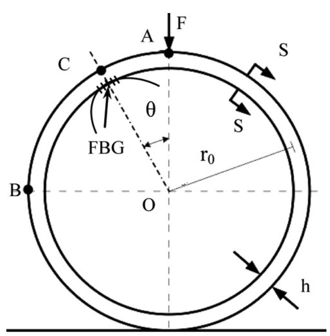


Figure 19 Schematic diagram of a thin-walled ring



with different displacements. This structure is insensitive to ambient temperature changes, which makes it more suitable for practical applications. Compared with the cantilever or other support beams, this structure is more compact and simple. However, high sensitivity and large displacement measurement range cannot be achieved simultaneously due to the use of the ring-shape structure. Therefore, a long grating is needed for tiny displacement measurement with a high sensitivity and a short grating for large displacement measurement.

To sum up, although these temperature-insensitive sensors can obtain the relatively better effect of temperature compensation, their common characteristic is to detect the reflection spectrum broadening of the FBG. It is well known that the profile of the broadened spectrum of FBG is usually irregular due to the nonuniform strain on the grating. Therefore, it is difficult to precisely obtain the bandwidth of the CFBG, which maybe bring some errors in the practical application. Furthermore, most of these sensors of detecting bandwidth need more complex demodulation schemes.

5. Fiber Bragg grating displacement sensors based on other detection principles

There are FBG displacement sensors based on other detection principles. Of these, this paper discusses mainly two types of FBG displacement sensors for the principles of intensity detection and phase detection.

5.1 Intensity detecting sensors

The basic principle of the intensity modulation fiber grating sensor is to convert the wavelength shift into an intensity variation, which can use it to determine the wavelength position of the sensor (Zhao and Liao, 2004; Dong and Tam, 2008). Based on the edge filter demodulation approach (Melle *et al.*, 2002), Zou demonstrated the use of an FBG displacement sensor based on an asymmetric twin-core fiber (Zou *et al.*, 2012). The schematic diagram of the sensing head and the demodulation filter are shown in Figure 21. The edge filter is formed by the fusion splicing of a segment of the twin-core fiber between two standard single-mode fibers, which converts the wavelength shift into an intensity variation. The experimental results indicate that the change in external displacement varied linearly with the output intensity of the sensor, and the displacement can be obtained by measuring the intensity. As mentioned earlier in the text, this proposed sensor adopted an edge filter which makes the output intensity closely related to the central wavelength of input signal, and it has some advantages such as quick response and a relatively simple structure, but the introduction of spring will lower the sensitivity, accuracy and stability of the whole system.

5.2 Phase detecting sensors

The unbalanced Mach–Zehnder interferometer (MZI) demodulation method (Kersey *et al.*, 1992; Weis *et al.*, 1994) is a parametric conversion demodulation method, which converts the wavelength shift of the sensing grating into phase variation which can be used for detection. Based on this method, an improved high-sensitive FBG displacement sensor which used a slow light interferometer had has proposed (Zhang *et al.*, 2014). The FBG micro displacement sensor of the Omega-like beam structure is shown in Figure 22(a). The displacement could be

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Figure 20 (a) The reflection spectra of the FBG with different displacements; (b) bandwidth variations versus the displacement for different grating lengths

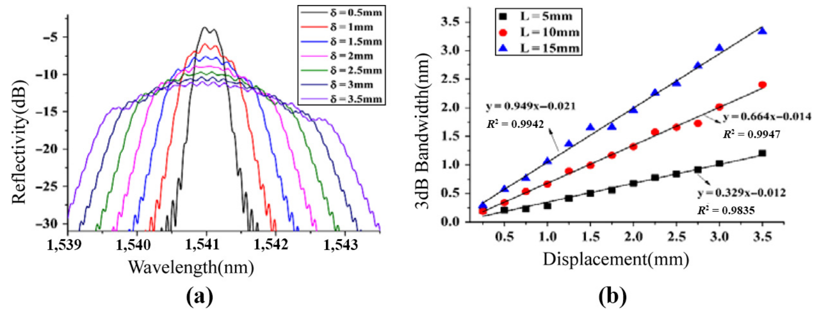


Figure 21 (a) Schematic diagram of the sensing head; (b) schematic diagram of the twin-core demodulation filter

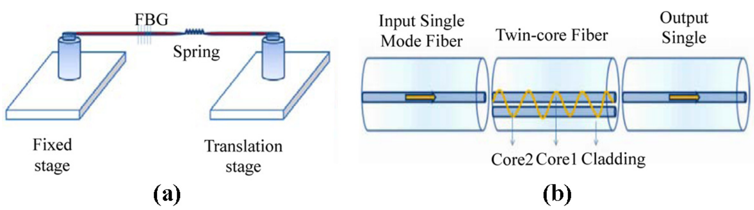
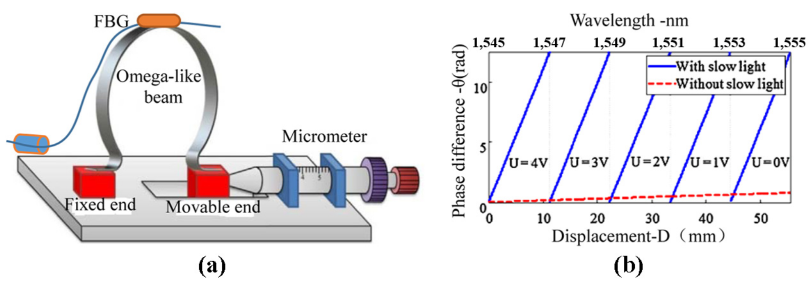


Figure 22 (a) FBG micro displacement sensor with omega-like beam structure; (b) relationship between the output phase difference and the measured displacement



measured by monitoring the output phase of the MZI. The relationship between the phase difference of the output and the measured displacement is presented in Figure 22(b). There exists a problem that trade-off between the sensitivity and the corresponding demodulation ranges. Although the optical fiber MZI based on slow light (Vlasov *et al.*, 2005; Zhang *et al.*, 2007) in polymer-infiltrated PCW (PI-PCW) was proposed to enhance the demodulation sensitivity of the sensor, the range of measurement is reduced and the problem of cross-sensitivity has not been solved, which make it unfeasible in practical applications. Therefore, the future task is toward the further design of FBG sensing system with a higher measurement ranges and the temperature-insensitive FBG displacement sensor.

In addition to the sensors mentioned above, there are other types of sensors. Based on the Fabry-Pérot (F-P) effect of FBG, a temperature-insensitive FBG displacement sensor and a peak wavelength demodulation method were presented (Tao *et al.*, 2017). The displacement sensor has a high sensitivity of 117 pm/mm and an accuracy of 0.085 mm within a range of 0-2 mm, which has more considerable potential applications as a long gauge sensor in practical civil engineering structures. As depicted in Figure 23, an apodized grating was attached at a specific position on the inner surface of a thin-walled ring. When the ring is deformed, the FBG is divided into two segments of identical FBGs but oppositely directed chirp gradients. From this, the F-P cavity within the grating area can be constructed, and the resonant peaks can be observed in the reflection spectrum. Figure 24 shows the reflection spectra with

Figure 23 Schematic diagram of the thin-walled ring

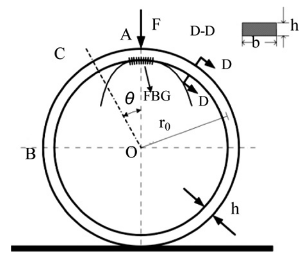
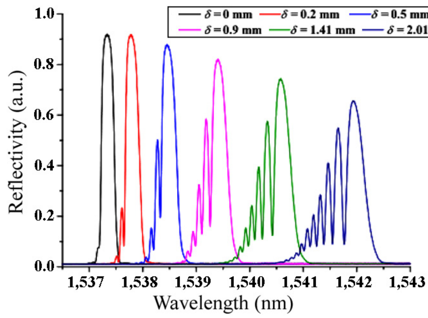


Figure 24 The simulated reflection spectra of the CFBG with different displacements



different displacements of the stress point of the ring. The wavelength separation between the wavelengths of the resonant peaks changes linearly with displacement variation, whereas this separation is insensitive to temperature variation. Although the fiber structure is compact and temperature independent, the range of measurement is limited by the structure. Moreover, there exists some errors due to only use part of the spectrum which could result in a large inaccuracy in experimental measurement.

To sum up these two sections, the main characteristics (i.e. range of measurement, sensitivity and resolution) of the FBG displacement sensors based on different methods of signal demodulation, such as reflected bandwidth demodulation, out optical intensity demodulation, phase demodulation and peak wavelength demodulation are summarized in Table II.

6. Conclusion

This paper analyzes and summarizes the FBG displacement sensor technology developed in recent years. The current research is mainly focused on the sensing method, the design and construction of the elastic structure and the design of new information detection method.

As FBG sensing is a new technology, its state is not completely mature. The sensing characteristics and technology need a long time to be researched and developed. But with the rapid development of science and technology, requirements for precised measurement should be urgently improved. Therefore, high sensitivity, high precision, large ranges, high reliability and other characteristics are the main trends for development of FBG displacement sensors. The following research field will be strengthened in the future:

- Temperature compensation technology of FBG displacement sensors based on wavelength demodulation: Current research reports do not take the real-time problems of temperature compensation into consideration. In particular, when the displacement measurement grating and temperature compensated grating are packaged differently, their response times to ambient temperature changes vary so as to make it inaccurate for temperature compensation. There is a growing interest in conducting research on real-time and accurate temperature-compensated displacement sensor, which can be applied in situations where temperature changes frequently.
- A study of more diverse elastic structures: Most of the existing displacement sensor configurations are based on the external packaging structure of cantilever beams, the volume of which is larger. Today, there is an increasing trend toward miniaturization and integration of multiple sensor technologies. Therefore, there will be increased focus on new elastic configurations, such as all-fiber structures.
- With the rapid development in the field of optical fiber manufacturing technology, special fibers (micro- and nano-fibers, photonic crystal fibers, etc.) with greater tensile strength, smaller diameter and better property are

Table II Performances and SHM applications for FBG displacement sensors

Reference	Method of signal demodulation	Application field	Range (mm)	Sensitivity	Resolution (μm)
Zhang *et al.* (2008)	Reflected bandwidth demodulation	Building and Bridge	0 ~ 6	50 pm/mm	/
Wei *et al.* (2011)	Reflected bandwidth demodulation	General purpose	0~8.5	480 pm/mm	200
Dong *et al.* (2005)	Reflected bandwidth (or Intensity) demodulation	General purpose	0 ~ 13 (or 0 ~ 9)	356.4 pm/mm (or 37.9 mv/mm)	/
Shen and Zhong (2011)	Reflected bandwidth demodulation	General purpose	0 ~ 20	58 pm/mm	344.8
Zhong *et al.* (2012)	Reflected bandwidth (or Intensity) demodulation	General purpose	0 ~ 15 (0 ~ 11)	250 pm/mm (or 3.7 mW/mm)	80
Zhao *et al.* (2008)	Reflected bandwidth demodulation	Oil and gas industry, seismic investigation and oil exploration	0 ~ 1.0	/	/
Tao *et al.* (2016)	Reflected bandwidth demodulation	Civil, industrial and military structures	0 ~ 3.5	567 pm/mm	40
Zou *et al.* (2012)	Intensity demodulation	Building and Bridge	0 ~ 10	/	/
Zhang *et al.* (2014)	Phase demodulation	General purpose	0 ~ 55.6	1.035 rad/mm	/
Tao *et al.* (2017)	Peak wavelength demodulation	Civil engineering structures	0 ~ 2	117 pm/mm	85

being developed. Fiber gratings manufactured with such special fibers will greatly improve the performance of the sensors.

In the near future, FBG displacement sensing technologies will be more mature and reach the state of traditional electromagnetic displacement sensing technology, which will play a significant role in the field of SHM.

References

Chen, J.A., Huang, D., Zhao, H.T., Wang, Q.B., Qiu, Y. and Duan, D.P. (2013), "Fiber Bragg grating-based plane strain monitoring of aerostat envelope structures", *Applied Optics*, Vol. 52 No. 19, pp. 4631-4639.

Chen, S.M., Liu, Y., Liu, X.X., Zhang, Y. and Peng, W. (2015), "Self-compensating displacement sensor based on hydramatic structured transducer and fiber Bragg grating", *Photonic Sensors*, Vol. 5 No. 4, pp. 351-356.

Cui, L.Z., Jiang, Y. and Liu, Y.H. (2011), "A fiber optic displacement sensor with temperature compensation", *Acta Photonica Sinica*, Vol. 40 No. 11, pp. 1667-1670.

Dong, X.Y. and Tam, H.Y. (2008), "A novel temperature-compensated, intensity-modulated fiber Bragg grating sensor system". Optical Fiber Sensors Conference, 2008. APOS'08. 1st Asia-Pacific. *IEEE*, pp. 1-4.

Dong, X.Y., Liu, Y.Q., Liu, Z.G. and Dong, X.Y. (2001), "Simultaneous displacement and temperature measurement with cantilever-based fiber Bragg grating sensor", *Optics Communications*, Vol. 192 Nos 3/6, pp. 213-217.

Dong, X.Y., Yang, X.F., Zhao, C.L. and Ding, L. (2005), "A novel temperature-insensitive fiber Bragg grating sensor for displacement measurement", *Smart Materials and Structures*, Vol. 14 No. 2, pp. 7-10.

Fu, D., Li, H.W., Leng, Z.P., Li, L. and Jin, X.Y. (2009), "Research and design of self-compensation FBG-based displacement sensor for structural health monitoring", *Low Temperature Architecture Technology*, Vol. 31 No. 6, pp. 1-5.

Guan, B.O.U., Liu, Z.G., Kai, G.Y. and Dong, X.Y. (1999), "Fiber Bragg grating displacement sensor based on a cantilever beam", *Acta Photonica Sinica*, Vol. 28 No. 11, pp. 983-985.

Guo, Y.X., Xiong, L., Kong, J.Y., Zhang, Z.Y. and Qin, L. (2017), "Sliding type fiber Bragg grating displacement sensor", *Optics and Precision Engineering*, Vol. 25 No. 1, pp. 50-58.

Guo, Y.X., Zhang, D.S., Fu, J.J., Liu, S.B., Zhang, S.Z. and Zhu, F.D. (2015), "Development and operation of a fiber Bragg grating based online monitoring strategy for slope deformation", *Sensor Review*, Vol. 35 No. 4, pp. 348-356.

Guo, Y.X., Kong, J.Y., Liu, H.H., Xiong, H.G., Li, G.F. and Qin, L. (2016), "A three-axis force fingertip sensor based on fiber Bragg grating", *Sensors and Actuators A: Physical*, Vol. 249, pp. 141-148.

Han, Y.G., Dong, X.Y., Lee, J.H. and Lee, S.B. (2006), "Wavelength-spacing-tunable multichannel filter incorporating a sampled chirped fiber Bragg grating based on a symmetrical chirp-tuning technique without center wavelength shift", *Optics Letters*, Vol. 31 No. 24, pp. 3571-3573.

He, J., Dong, H.J., Zhou, Z. and Zhang, G.Y. (2010), "A kind of new displacement sensor based on FBG for engineering", *Journal of Harbin University of Science and Technology*, Vol. 15 No. 5, pp. 61-64.

Housner, G.W., Bergman, L.A., Caughey, T.K. and Chassiakos, A.G. (1997), "Structural control: past, present, and future", *Journal of Engineering Mechanics*, Vol. 123 No. 9, pp. 897-971.

Javdani, S., Fabian, M., Carlton, J.S., Sun, T. and Grattan, K. T.V. (2016), "Underwater free-vibration analysis of full-scale marine propeller using a fiber Bragg grating-based sensor system", *IEEE Sensors Journal*, Vol. 16 No. 4, pp. 946-953.

Jiang, S.C., Wang, J., Sui, Q.M. and Cao, Y.Q. (2015), "A novel wide measuring ranges FBG displacement sensor with variable measurement precision based on helical bevel gear", *Optoelectronics Letters*, Vol. 11 No. 2, pp. 81-83.

Jiang, S.C., Wang, J., Sui, Q.M., Wang, Z.F., Wang, N. and Cao, Y.Q. (2013), "Developing of micro FBG displacement sensor and its application to model experiment", *Journal of Disaster Prevention and Mitigation Engineering*, Vol. 33 No. 3, pp. 348-353.

Kersey, A.D., Berkoff, T.A. and Morey, W.W. (1992), "High-resolution fibre-grating based strain sensor with interferometric wavelength-shift detection", *Electronics Letters*, Vol. 28 No. 3, pp. 236-238.

Kim, J.H., Bae, J.K., Han, Y.G., Han, Y.G., Kim, S.H., Jeone, J.M. and Lee, S.B. (2004), "Effectively tunable dispersion compensation based on chirped fiber Bragg gratings without central wavelength shift", *IEEE Photonics Technology Letters*, Vol. 16 No. 3, pp. 849-851.

Li, J.C., Neumann, H. and Ramalingam, R. (2015), "Design, fabrication, and testing of fiber Bragg grating sensors for cryogenic long-ranges displacement measurement", *Cryogenics*, Vol. 68, pp. 36-43.

Li, T.L., Shi, C.Y. and Ren, H.L. (2017a), "A novel fiber Bragg grating displacement sensor with a sub-micrometer resolution", *IEEE Photonics Technology Letters*, Vol. 29 No. 14, pp. 1199-1202.

Li, T.L., Tan, Y.G., Shi, C.G., Guo, Y.X., Najdovski, Z., Ren, H.L. and Zhou, Z.D. (2017b), "A high-sensitivity fiber Bragg grating displacement sensor based on transverse property of a tensioned optical fiber configuration and its dynamic performance improvement", *IEEE Sensors Journal*, Vol. 17 No. 18, pp. 5840-5848.

Li, W.L., Zhang, Y.X., Wang, Q., Pan, J.J., Liu, J. and Zhou, C.M. (2012), "Displacement monitor with FBG deforming ring and its application in high speed railway", OFS2012 22nd International Conference on Optical Fiber Sensor, 2012, *International Society for Optics and Photonics*, *Beijing*.

Melle, S.M., Liu, K. and Measures, R.M. (2002), "A passive wavelength demodulation system for guided-wave Bragg grating sensors", *IEEE Photonics Technology Letters*, Vol. 4 No. 5, pp. 516-518.

Mi, H.K. and Nan, Q.M. (2011), "Study on magnetic coupling FBG displacement sensor". International Conference on Mechatronics and Automation. *IEEE*, pp. 2443-2447.

Panopoulou, A., Loutas, T., Roulias, D., Fransen, S. and Kostopoulos, V. (2011), "Dynamic fiber Bragg gratings based health monitoring system of composite aerospace structures", *Acta Astronautica*, Vol. 69 Nos 7/8, pp. 445-457.

Ramly, R., Kuntjoro, W. and Rahman, M.K.A. (2012), "Using embedded fiber Bragg grating (FBG) sensors in smart aircraft structure materials", *Procedia Engineering*, Vol. 41, pp. 600-606.

Shen, C.Y. and Zhong, C. (2011), "Novel temperature-insensitive fiber Bragg grating sensor for displacement measurement", *Sensors and Actuators A: Physical*, Vol. 170 Nos 1/2, pp. 51-54.

Tao, S.C., Dong, X.P. and Lai, B.W. (2016), "Temperature-insensitive fiber Bragg grating displacement sensor based on a thin-wall ring", *Optics Communications*, Vol. 372, pp. 44-48.

Tao, S.C., Dong, X.P. and Lai, B.W. (2017), "A sensor for simultaneous measurement of displacement and temperature based on the Fabry-Pérot effect of a fiber Bragg grating", *IEEE Sensors Journal*, Vol. 17 No. 2, pp. 261-266.

Tian, X.D., Zhang, H.X., Liu, W.Y. and Fan, J.G. (2016), "Temperature compensated optical fiber grating displacement sensor", *Chinese Journal of Electron Devices*, Vol. 39 No. 3, pp. 576-580.

Vlasov, Y.A., O'boyle, M., Hamann, H.F. and McNab, S.J. (2005), "Active control of slow light on a chip with photonic crystal waveguides", *Nature*, Vol. 438 No. 7064, pp. 65-69.

Wang, J.J., Fu, X.H., Jiang, D.S. and Zhang, F.T. (2007), "Research of differential optical fiber grating displacement cell and it's temperature characteristic", *Journal of Wuhan University of Technology*, Vol. 29 No. 12, pp. 112-115.

Wei, T., Qiao, X.G. and Jia, Z.A. (2011), "Simultaneous sensing of displacement and temperature with a single FBG", *Optoelectronics Letters*, Vol. 7 No. 1, pp. 26-29.

Weis, R.S., Kersey, A.D. and Berkoff, T.A. (1994), "A four-element fiber grating sensor array with phase-sensitive detection", *IEEE Photonics Technology Letters*, Vol. 6 No. 12, pp. 1469-1472.

Yazdizadeh, Z., Marzouk, H. and Hadianfard, M.A. (2017), "Monitoring of concrete shrinkage and creep using fiber Bragg grating sensors", *Construction and Building Materials*, Vol. 137, pp. 505-512.

Zhang, J.L., Yu, C.X., Wang, K.R. and Zeng, J.Y. (2008), "Displacement sensor with temperature compensation based on chirp fiber grating", *Acta Optica Sinica*, Vol. 28 No. 4, pp. 779-782.

Zhang, W.G., Dong, X.Y., Zhao, Q.D., Kai, G.Y. and Yuan, S.Z. (2001), "FBG-type sensor for simultaneous measurement of force (or displacement) and temperature based on bilateral cantilever beam", *IEEE Photonics Technology Letters*, Vol. 13 No. 12, pp. 1340-1342.

Zhang, Y.D., Wong, W., Yu, B. and Yuan, P. (2007), "Technology of slow light in photonic crystal waveguides", *Laser & Optoelectronics Progress*, Vol. 44 No. 10, pp. 26-32.

Zhang, Y.J., Huang, B.K., Wei, B., Jia, B.B. and Bi, W.H. (2011), "Experiment research in slope monitoring based on fiber Bragg grating sensing technology", *Optical Technique*, Vol. 37 No. 2, pp. 208-212.

Zhang, Y.N., Zhao, Y. and Wang, Q. (2014), "Improved design of slow light interferometer and its application in FBG displacement sensor", *Sensors and Actuators A: Physical*, Vol. 214, pp. 168-174.

Zhao, Y. and Liao, Y.B. (2004), "Discrimination methods and demodulation techniques for fiber Bragg grating sensors", *Optics and Lasers in Engineering*, Vol. 41 No. 1, pp. 1-18.

Zhao, Y., He, H. and Qi, W. (2011), "Interrogation technique using a novel spectra bandwidth measurement method with a blazed FBG and a fiber-optic array for an FBG displacement sensor", *Sensors and Actuators A: Physical*, Vol. 165 No. 2, pp. 185-188.

Zhao, Y., Liao, Y.B. and Lai, S.R. (2002), "Simultaneous measurement of down-hole high pressure and temperature with a bulk-modulus and FBG sensor", *IEEE Photonics Technology Letters*, Vol. 14 No. 11, pp. 1584-1586.

Zhao, Y., Yu, C.B. and Liao, Y.B. (2004), "Differential FBG sensor for temperature-compensated high-pressure (or displacement) measurement", *Optics & Laser Technology*, Vol. 36 No. 1, pp. 39-42.

Zhao, Y., Zhao, H.W., Zhang, X.Y., Meng, Q.Y. and Yuan, B. (2008), "A novel double-arched-beam-based fiber Bragg grating sensor for displacement measurement", *IEEE Photonics Technology Letters*, Vol. 20 No. 15, pp. 1296-1298.

Zhao, Z.G., Zhang, Y.J., Li, C., Wan, Z., Li, Y.N. and Wang, K. (2015), "Monitoring of coal mine roadway roof separation based on fiber Bragg grating displacement sensors", *International Journal of Rock Mechanics and Mining Sciences*, Vol. 74, pp. 128-132.

Zhong, C., Shen, C.Y., Chu, J.L., Zou, X., Li, K., Jin, Y.X. and Wang, J.F. (2012), "A displacement sensor based on a temperature-insensitive double trapezoidal structure with fiber Bragg grating", *IEEE Sensors Journal*, Vol. 12 No. 5, pp. 1280-1283.

Zou, Y., Dong, X.P., Lin, G.B. and Adhami, R. (2012), "Wide ranges FBG displacement sensor based on twin-core fiber filter", *Journal of Lightwave Technology*, Vol. 30 No. 3, pp. 337-343.

Corresponding author

Yongxing Guo can be contacted at: yongxing_guo@wust.edu.cn