Multicore fibers for sensing applications

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**NANYANG
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**MULTICORE FIBERS FOR SENSING
APPLICATIONS**

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MULTICORE FIBERS FOR SENSING APPLICATIONS

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Abstract

Multicore fibers (MCFs) are optical fibers which have several cores integrated into a common cladding. As one type of space-division multiplexing, MCFs have been widely investigated in optical communication to improve the data capacity limit. Due to the intrinsic advantages such as small size, well-defined core separation, improved isothermal behaviour, light weight, immunity to electromagnetic interference, MCFs have also attracted extensive interests for optical sensing applications. This thesis focuses on investigating and fabricating MCF-based sensors with high performances by post-processing techniques such as inscribing gratings or introducing helical structures into the MCFs.

In this thesis, we first review the background knowledge and development of MCF-based sensors. And then we detail the working principles, fabrication methods and experimental results of three sensors based on a heterogeneous MCF.

The first one is a directional bending sensor based on a heterogeneous MCF with fiber Bragg gratings (FBGs). To date, several types of sensors based on FBGs inscribed in homogeneous MCFs have been reported. However, due to the homogeneous properties of the multiple cores, simultaneous interrogation of the FBGs in the multiple cores demands high precision and cumbersome alignment with, for example, a coupler and a ball lens, or customized and complicated fan-out devices. Therefore, to realize an easier interrogation of the FBGs in different cores, we propose to inscribe FBGs in heterogeneous MCFs. As the heterogeneous MCFs have non-identical cores, FBGs with different resonant wavelengths can be written simultaneously into the multiple cores in only one process with the scanned phase mask method. The MCF we used has a center core and six identical outer cores located respectively at the corners of a regular hexagon. The refractive index of the center core is a little lower than that of the outer cores. Due to the refractive index difference between the center core and outer cores, the FBGs with obviously different central wavelengths can be measured by only splicing a segment of a multimode fiber (MMF) between the MCF and the lead-in single mode fiber (SMF). The curvature sensitivity of the FBG in the outer core

depends on the bending orientation in the form of a sine function. The maximum linear curvature sensitivity is about 0.128 nm/m^{-1} . The proposed sensor offers advantages of flexibility in fabrication, simple interrogation, and capability of eliminating the cross-sensitivity to temperature or externally applied axial strain.

The second one is a highly sensitive strain sensor based on a helical structure (HS) fabricated in the MCF. The MCF was locally twisted into an HS permanently by a CO_2 laser splicing system and then spliced between two short sections of MMFs to construct an in-line Mach-Zehnder interferometer. In the region of the HS, the outer cores were deformed into helical cores while the center core was kept straight. Due to the HS, a maximum strain sensitivity as high as $-61.8 \text{ pm}/\mu\epsilon$ was experimentally achieved. It is the highest sensitivity among interferometer-based strain sensors reported so far, to the best of our knowledge. Moreover, the proposed sensor has the ability to discriminate axial strain and temperature, and offers several advantages such as repeatability of fabrication, robust structure, and compact size, which further benefits its practical sensing applications.

Based on the MCF with the HS, we also propose and demonstrate a sensor for directional torsion and temperature discrimination. By introducing the short HS, the fiber circular asymmetry was achieved, which made the sensor have the ability of twist direction discrimination. The maximum torsion sensitivity of the proposed sensor reaches $-0.118 \text{ nm}/(\text{rad/m})$ for the twist range from -17.094 rad/m to 15.669 rad/m . Compared with the previously reported torsion sensor schemes utilizing micro-machining means, the proposed sensor not only owns the capability of the discrimination of directional torsion and temperature but also takes the merits of easy fabrication and good mechanical robustness.

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List of Abbreviations

BLS	Broadband Light Source
BPM	Beam Propagation Method
CCW	Counterclockwise
CT	Capillary Tube
CW	Clockwise
EFPI	Extrinsic Fabry-Perot Interferometer
FBG	Fiber Bragg Grating
FCF	Four-Core Fiber
FFT	Fast Fourier Transform
FMF	Few-Mode Fiber
FPI	Fabry-Perot Interferometer
FSR	Free Spectrum Range
HLPFG	Helical Long-Period Fiber Grating
HS	Helical Structure
HW	Helical Waveguide
IFPI	Intrinsic Fabry-Perot Interferometer
IoT	Internet of Things
LPFG	Long-Period Fiber Grating
MCF	Multicore Fiber
MDM	Mode Division Multiplexing
MI	Michelson Interferometer
MMF	Multimode Fiber
MZI	Mach-Zehnder Interferometer
NA	Numerical Aperture
OC	Optical Circulator
OFS	Optical Fiber Sensor
OPD	Optical Path Difference
OSA	Optical Spectrum Analyser

PCF	Photonic Crystal Fiber
PMF	Polarization-Maintaining Fiber
PML	Perfect Match Layer
SDM	Space Division Multiplexing
SMF	Single Mode Fiber
SSMF	Seven Single Mode Fiber
TCF	Twin-Core Fiber
WDM	Wavelength-Division Multiplexing

Chapter 1 Introduction

This chapter introduces the background of optical fibers and multicore fibers (MCFs) based sensors. The motivation and objectives of this project are clarified. Finally, the thesis outline is presented.

1.1 Background

The concept of guiding light via total internal refraction dates back to the 1840s, physicists Daniel Colladon and Jacques Babinet demonstrated that light could be guided in water jets, and Jacques Babinet extended the principle of the light guiding along bent glass rods [1]. However, fiber optics was utilized for practical applications until the 1950s. Narinder S. Kapany and Harold H. Hopkins, and Abraham C. S. Van Heel almost simultaneously reported the creation of transporting optical image with fiber bundles for medical applications in 1954 [2, 3]. In the 1960s, the laser invention generated a wave of research interest in transmitting information with light. In 1961, Elias Snitzer reported a theoretical description of single mode fibers (SMFs) which could transmit light with only one mode [4]. However, at that time, the loss of the fibers was too large for optical communication. In 1964, Charles K. Kao and George Hockham theoretically demonstrated that the loss in optical fibers could be decreased dramatically below 20 dB/km by removing the impurities, which would make optical fibers possible for long distance optical communication [5]. This work, which made optical fibers as the practical transmission medium in optical fiber communication, is now recognized as the beginning of the optical fiber revolution. Charles K. Kao won the 2009 Nobel prize in physics for his contribution to optical fiber communication. In 1970, the first fiber with a loss less than 20 dB/km was demonstrated by the scientists Robert Maurer, Donald Keck, and Peter Schultz from Corning [6]. During the following few years, with the accelerated development of fiber design and fabrication, the fiber loss decreased dramatically. By 1979, the optical fiber loss dropped to 0.2 dB/km at the wavelength of 1550 nm [7]. Subsequently, optical fibers have been widely

used for fiber lasers [8], sensing applications [9], optical fiber communications [10] and become the backbone of the global telecommunication systems.

By definition, the simplest basic structure of a conventional silica optical fiber consists of a core, a cladding, and a coating layer, as shown in Fig. 1.1. It is a cylindrical waveguide. The refractive index of the core n_{core} is larger than that of the cladding. This type of fibers are generally referred to step-index fibers. The light is guided in the fiber core through total internal reflections. The coating layer is used to enhance the mechanical strength of the fiber and protect it from the physical damage.

Figure 1.1. Cross-sectional schematic diagram of an optical fiber basic structure.

Figure 1.2. Schematic diagram of total internal reflection in an optical fiber.

Figure 1.2 illustrates the case of the light incident on the fiber end face from the air. Assuming that the incident angle from the air to the fiber is θ_1 , the angle of the refraction is θ_2 , the incident angle at the interface between the cladding and the core is φ . The refractive indices of the air, the core, and the cladding are $n_A, n_{core}, n_{cladding}$, respectively. According to Snell's law for the optical fiber, we have:

$$n_A \sin(\theta_1) = n_{core} \sin(\theta_2) \quad (1.1)$$

The critical angle φ_c for total internal reflection is defined as:

$$\sin(\varphi_c) = n_{cladding} / n_{core} . \quad (1.2)$$

When $\varphi > \varphi_c$, the light ray will reflect totally at the core-cladding interface and propagate along the fiber core. The standard measure of the light-acceptance of the optical fiber is defined as numerical aperture (NA). Since $n_A \approx 1$,

$$NA = n_A \sin(\theta_1) = \sqrt{n_{core}^2 - n_{cladding}^2} . \quad (1.3)$$

The guiding properties of an optical fiber can be characterized by V parameter (normalized frequency) which is defined as [11]:

$$V = \frac{2\pi}{\lambda} a NA. \quad (1.4)$$

The designed fibers with $V < 2.405$ can only support one mode, which is called SMFs.

The progress in the fields of optical fibers, optical fiber devices, and optoelectronic instruments, especially the key components in optical fiber communication systems such as light sources, optical spectrum analysers, optical signal interrogators and photodetectors, has contributed to significantly decreasing the cost of optical fiber sensors (OFSs) and helped promote the development and widespread applications of OFSs. OFSs have a number of advantages. For example, the small size of OFSs enables them to be easily embedded into the structures of the objects under monitoring; all-optical signal feature makes them immune to electromagnetic interference. Also, they have a light weight, a simple interrogation for remote sensing, good repeatability, high

sensitivities, capability of monitoring multiple environmental parameters, and ability of point, quasi-distributed or distributed sensing, etc. Due to these intrinsic advantages, OFSs have been widely used as the sensors for monitoring temperature [12], humidity [13], strain [14], bending [15], vibration [16], gas pressure [17], refractive indices of liquids [18, 19], fluid level [20], water flow [21], current [22] and magnetic field [23] and so on. Such widespread applications of OFSs show their great potential for the Internet of Things (IoT) referring to the technologies which make things sense each other and their surrounding environment [24]. As an important part of the new generation of information technology, IoT will play an important role in our daily life.

With the fast development of the information technology in recent decades, the communication capacity demand has been increased dramatically. Over the past four decades, the capacity of an SMF has risen by about ten times every four years. Transmission technologies breakthroughs have been able to keep up with the exponential growth of the Internet data traffic. Nowadays, the communication capacity demand can be satisfied by SMF-based wavelength-division multiplexing (WDM) systems. However, it is estimated that the WDM systems will reach their Shannon capacity limit in the next decade or so [25]. The capacity of an SMF typically increases with the transmitted power, but optical fibers are Kerr nonlinear mediums, the transmitted signal with high power results in the refractive index change of the fiber core by the Kerr nonlinear effect, which will result in distortion of the WDM channels [26]. The capacity limit is not particular to a certain transponder standard or modulation format. For an SMF, the capacity limit is 100 Tbit/s [25]. Therefore, to keep up with the data traffic demand, more SMFs will be needed. Without further innovative techniques, the communication system with parallel fibers will make the energy consumption and cost increase linearly with the capacity [25].

To overcome the Shannon capacity limit of SMF-based WDM systems, a solution is to utilize space division multiplexing (SDM) which has attracted extensive research interests in recent years [25]. The idea of using SDM to increase the capacity of an optical fiber dates back to almost 40 years ago [27]. In SDM systems, several different signals can be transmitted simultaneously through multiple spatially distinguishable

paths in a single fiber. Basically, there are two methods to introduce multiple signal paths into a single fiber. The first one is based on weakly-coupled MCFs which contain several separate cores, and all the adjacent cores have sufficiently low crosstalk. In 1979, S. Iano *et al.* proposed the first and most obvious method of implementing SDM by utilizing weakly-coupled MCFs [27]. The second approach is based on mode division multiplexing (MDM), which was proposed by S. Berdague *et al.* in 1982 [28]. MDM-based approach can be realized by using few-mode fibers (FMFs) or multimode fibers (MMFs) or strongly-coupled MCFs. In a strongly-coupled MCF, the larger crosstalk between the adjacent cores is purposely designed by decreasing the distances between the adjacent cores. Due to supporting several super-modes, strongly-coupled MCFs can be considered as a type of MMFs. In MDM-based systems, because of the mode dispersion, different modes exhibit different mode group delays, complex multiple-input-multiple-output digital signal processing techniques are required at the receiver [29]. Weakly-coupled MCF-based SDM is a promising and straightforward method to improve the transmission capacity of a single fiber. To further improve the spatial channel number of SDM fibers, the way of combining weakly-coupled MCFs and FMF concepts (i.e. each core of the MCFs can support a few modes) has also been demonstrated [30-32].

Thanks to MCFs attracting considerable interests, the fabrication methods and types of MCFs have been extensively developed in the last decade. From the core point of view, MCFs can be mainly classified into two categories, namely homogenous MCFs and heterogeneous MCFs. All the cores of a homogenous MCF are identical. For a heterogeneous MCF, there are two or more distinct cores. In the past few years, MCF-based sensors have become a very attractive research topic, due to their intrinsic advantages, for example, multiple channels, well-defined core separation, small size, light weight, repeatability, etc. MCFs have further advantages over bundles of fibers because all the cores of an MCF share the same cladding, which means that MCFs have an improved isothermal behaviour. MCF-based sensors can be utilized for sensing temperature, axial strain, directional bending, twist and 3D shape, and so on. So far, there are a few methods of implementing MCF-based sensors, such as fabricating fiber

Bragg gratings (FBGs), long-period fiber gratings (LPFGs), or in-line Mach-Zehnder interferometers (MZIs) in MCFs.

1.2 Motivation and objectives

FBGs are widely utilized as strain and temperature sensors. Generally, the practical sensing applications of FBGs in conventional SMFs often encounter an issue, i.e. cross-sensitivities. For instance, since FBGs respond sensitively to both temperature and strain changes, the temperature-strain cross-sensitivity has to be eliminated when monitor strain or temperature. To solve the problem of cross-sensitivities, a few methods have been proposed and demonstrated, for instance, utilizing the combination of axially arrayed an LPFG and an FBG [33], two FBGs with different diameters [34], dual-wavelength superimposed FBGs [35]. However, these methods increased the sensor complexities, and the applied temperature perturbation may be non-uniform for the axially arrayed gratings, which will affect the sensing accuracy. Since all the cores of an MCF are integrated into a common cladding, all the cores can experience the same temperature perturbation at any particular positions along the MCF. Thus, the cross-sensitivities between temperature and other parameters can be eliminated for MCF-based sensors. In recent decade, there is an extensive interest in expanding the sensing applications of MCFs. MCFs with FBGs have been widely used for fabricating various types of sensors, especially for monitoring multidimensional bending or 3D shape measurement. To date, almost all the previously reported MCFs for fabricating FBGs-based sensors are homogenous. Because of the two hurdles, the lens effect of the fiber cladding and the shadow effect, it is tough to fabricate FBGs with uniform Bragg wavelengths in different cores in homogeneous MCFs with lateral UV exposure. Many efforts have been previously made to improve the uniformity of the FBGs in different cores. However, the non-uniformity has not been eliminated. On the contrary, to avoid the two hurdles of the FBG fabrication in homogeneous MCFs, one way is to increase the wavelength difference between the FBGs in different cores. This goal can be realized by fabricating FBGs in heterogeneous MCFs.

Moreover, to collect the reflected signals of the FBGs in a homogeneous MCF, a complicated and expensive fan-out device is essential. On the contrary, due to the FBGs fabricated in heterogeneous MCFs having obviously different wavelengths, only splicing a segment of MMF between the MCF and the lead-in SMF can collect the reflected signals.

Strain measurement, one of the most important applications of OFSSs, has been widely applied in many fields, especially in structural health monitoring for aircrafts, dams, towers, bridges, skyscrapers, railways, highways, and so on. Fiber-based strain sensors have been demonstrated with various schemes, such as an FBG, an LPFG, or an MZI in different types of fibers including MCFs. Their sensitivities to strain were typically about 1 pm/ $\mu\epsilon$ for FBGs, less than 10 pm/ $\mu\epsilon$ for LPFGs or MZIs. Therefore, to further enhance the strain sensitivity, new designs are needed. Fabricating a helical structures (HS) in an MCF to form an MZI is an excellent choice to realize a strain sensor with a much higher strain sensitivity.

In addition, MCFs with HSs have other good sensing performances needed to be investigated. For instance, they can be used as torsion sensors. The twisted MCF-based torsion sensors have the ability to discriminate the clockwise and anticlockwise rotation of the fiber, and the temperature cross-sensitivity can be eliminated.

The objectives of this thesis are to explore and develop high-performance sensors based on MCFs by post-processing techniques such as grating fabrications or twisting MCFs. The first objective is to demonstrate our proposal of fabricating FBGs in a heterogeneous MCFs with a UV laser, collecting the reflected signals of different FBGs by utilizing a segment of MMF instead of a fan-out device, and then investigating its sensing performances and comparing the experimental results with theories. The second objective is to design and fabricate a novel strain sensor with a much higher strain sensitivity by introducing an HS into an MCF, and theoretically analyze its working principle. The third objective is to explore and investigate the sensing applications of the MCF with an HS.

1.3 Thesis outline

This thesis consists of 6 chapters. Chapter 1 introduces the background, motivation, and objectives of this project. Chapter 2 reviews the types of MCF-based sensors and their recent developments, as well as their working principles. Chapter 3 presents the background of fabricating FBGs in MCFs, and our work on inscribing FBGs in a heterogeneous MCF. A directional bending sensor based on the MCF with FBGs is demonstrated, the sensor exhibits the capability of eliminating the temperature or strain cross-sensitivities. Chapter 4 starts with the state-of-the-art of optical fiber strain sensors and then proposes a strain sensor with a much higher sensitivity based on an HS in an MCF. The process of fabricating HSs in a non-twisted MCF is introduced in detail. Based on the HS, an in-line MZI sensor with an ultra-high strain sensitivity is proposed and demonstrated. The proposed sensor has the ability to discriminate axial strain and temperature and offers several advantages such as repeatability of fabrication, robust structure, and compact size. Chapter 5 shows the experimental results of a directional torsion sensor with temperature discrimination based on the MCF with an HS. Compared with the previously reported torsion sensor schemes utilizing micro-machining means, the proposed sensor not only owns the capability of the discrimination of directional torsion and temperature but also takes the merits of easy fabrication and good mechanical robustness. Finally, Chapter 6 concludes this thesis and recommends the future work prospects in the research field for MCF-based sensors.

Chapter 2 Sensing Principles and Developments of MCF-based Sensors

MCFs have been reported as sensors based on various approaches such as FBGs, LPFGs, MZIs, Michelson interferometers (MIs), Fabry-Perot interferometers (FPIs). In this review chapter, the various approaches of implementing sensors based on MCFs and their working principles will be discussed.

2.1 FBGs in MCFs

Fiber gratings are a type of optical diffraction gratings [36], which have periodic structures along the fiber axis direction. From the period point of view, fiber gratings can generally be divided into two types, short-period gratings and LPFGs. Short period gratings also called FBGs, which have the capability of reflection. In an FBG, the light coupling occurs between the forward-propagating mode and the backward-propagating mode in the fiber core.

The phase condition for a fiber grating can be expressed as [36]

$$\beta_2 = \beta_1 + m \frac{2\pi}{\Lambda} \quad (2.1)$$

where β_1 , β_2 represent the propagation constants of the two coupling modes, respectively. Λ is grating period. Usually, the first order diffraction dominates in a fiber grating, and $m = -1$.

In an FBG, $\beta_1 = \beta_{core}$, $\beta_2 = -\beta_{core}$, where β_{core} denotes the propagation constant of the core mode. Since $\beta_{core} = 2\pi n_{eff,core} / \lambda$, where λ is the wavelength and $n_{eff,core}$ is the effective refractive index of the core mode, according to Eq. (2.1), the center wavelength of the reflected light of an FBG can be described as [36, 37]:

$$\lambda_B = 2n_{eff,core}\Lambda \quad (2.2)$$

2.1.1 Sensing principles of FBGs

When axial strain ε is applied to the fiber with a length l , the period Λ of the FBG and the effective refractive index $n_{eff,core}$ will be changed, which will cause a wavelength shift of the Bragg wavelength. ε is defined as $\varepsilon = \Delta l / l$, where Δl is the length change of the fiber. Because the axial strain is uniform along the fiber, the relative length change of the FBG, or the relative change of the period, will be equal to the relative change of the fiber, thus, $\varepsilon = \Delta l / l = \Delta \Lambda / \Lambda$. The wavelength shift of the FBG induced by the axial strain is given by [38, 39]:

$$\begin{aligned} \Delta \lambda_B &= 2 \left(\Lambda \frac{\partial n_{eff,core}}{\partial \varepsilon} + n_{eff,core} \frac{\partial \Lambda}{\partial \varepsilon} \right) \varepsilon \\ &= \lambda_B \left(\frac{1}{n_{eff,core}} \frac{\partial n_{eff,core}}{\partial \varepsilon} + \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial \varepsilon} \right) \varepsilon \end{aligned} \quad (2.3)$$

The axial strain induced grating period increment can be expressed by $\Delta \Lambda = \varepsilon \Lambda$, thus the second term in Eq. (2.3) equals to the unit. The refractive index change of the pure silica caused by photo-elastic effect can be described by [40-42]:

$$\Delta n_0 = -\frac{n_0^3[(1-\nu)p_{12} - \nu p_{11}]\varepsilon}{2} = p_\varepsilon n_0 \varepsilon \quad (2.4)$$

where $p_\varepsilon = -n_0^2[(1-\nu)p_{12} - \nu p_{11}]/2$ usually denotes the effective photo-elastic coefficient. p_{11} and p_{12} are photo-elastic coefficients, ν is the Poisson's ratio, and n_0 is the refractive index before applying strain to the fiber. The typical values for silica fibers are $p_{11} = 121$, $p_{12} = 0.270$ [43] and $\nu = 0.16$ [44]. For a typical germanosilicate optical fiber, p_ε is about -0.22 [45]. According to Eq. (2.4), the effective refractive index change of the core mode can be approximately described by $\Delta n_{eff} = p_\varepsilon n_{eff,core} \varepsilon$. Thus, the strain-induced Bragg wavelength shift can be further approximately rewritten as [46]:

$$\Delta \lambda_B = \lambda_B (1 + p_\varepsilon) \varepsilon \quad (2.5)$$

Due to the thermal-optic effect and thermal expansion effect, the temperature change will also result in the Bragg wavelength shift, which can be described as [47]:

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T \quad (2.6)$$

where $\alpha_\Lambda = (1/\Lambda)(\partial\Lambda/\partial T)$ is the thermal expansion coefficient for silica (about $0.55 \times 10^{-6} / ^\circ\text{C}$), $\alpha_n = (1/n)(\partial n/\partial T)$ represents the thermal-optic coefficient with a value of about $8.6 \times 10^{-6} / ^\circ\text{C}$. As α_n is much larger than α_Λ , the wavelength shift is mainly affected by the refractive index change.

If a fiber is bent with a curvature radius R , ε can be described by [41]:

$$\varepsilon = -Cx \quad (2.7)$$

where C is the curvature value, $C = 1/R$. x is a coordinate along a line connecting the curvature center and the fiber center, the positive direction is defined to be from the fiber center to the curvature center, the origin of the coordinate is at the center of the fiber. The part of the fiber at the inner side of the x positive direction will be compressed while the part at the outer side will be stretched. If two cores with FBGs of an MCF are used for bending sensing, when they lie at a certain position with different x values, the two FBGs will have different bending sensitivities. Considering the simplest case, when both the cores lie at the bending plane, the difference of the strain applied on the two FBGs can be given by:

$$\Delta\varepsilon = dC \quad (2.8)$$

where d is the distance between the two cores. Thus, the difference of the wavelength shifts of the two FBGs caused by the applied curvature C can be described by [48]:

$$\Delta\lambda = \lambda_B(1 + p_\varepsilon)dC \quad (2.9)$$

According to Eq. (2.5), Eq. (2.6), and Eq. (2.9), by monitoring the wavelength shift of the FBG, the applied strain, temperature variation, and curvature can be obtained, respectively.

2.1.2 Sensing applications of FBGs in MCFs

By inscribing FBGs, MCF-based sensors exhibit great potentials for sensing applications, especially for directional bending sensing or shape sensing. To date, several kinds of bending sensors based on FBGs in homogeneous MCFs have been proposed. For example, a single-axis bending sensor by utilizing FBGs in two cores of a four-core fiber (FCF) was experimentally demonstrated by M. J. Gander *et al.* in 2000 [48]. The cores of the FCF were nominally at the vertices of a square with the side of 52 μm . All the cores were designed for single mode operation over the wavelength range from 1300 nm to 1550 nm. Prior to FBG inscription, the FCF was photosensitized by hydrogen loading at 150 bar at room temperature for two weeks. Then FBGs were inscribed into two cores with the two-beam holographic technique [49]. The light was launched into the two gratings simultaneously with a 50:50 directional coupler and two standard SMFs. Since the core separation of the FCF was less than that of the two SMFs, a ball lens with a diameter of 2 mm was used to image the output from the coupler to the FCF. Then the reflections were coupled back into the coupler and combined into an SMF. When the two FBGs laid in the bending plane, the bending sensitivity was 48.9 pm/m^{-1} . And the FBGs showed temperature sensitivities of 10.3 pm/K and 10.4 pm/K , respectively.

In 2003, G. M. H. Flockhart *et al.* reported a two-axis curvature sensor with another type of FCF [50]. The cores located at the corners of a square with a core separation of about 44 μm . The cladding diameter was about 125 μm . The FBGs were inscribed into the cores simultaneously by utilizing scanned phase mask method. The end facet of the FCF was shown in Fig. 2.1 (a). The unstrained FBGs reflection spectra for the cores 1, 2, 3 were measured, as shown in Fig. 2.1(b), Fig. 2.1(c), and Fig. 2.1 (d), respectively. The differences among the reflection spectra of the three gratings were caused by the rotational alignment of the fiber relative to the UV laser beam and the uneven UV exposure during the grating inscription process. Since there was overlap between the three reflection spectra, a fan-out device was fabricated to interrogate each core independently. The sensor was able to monitor the curvature

magnitude and two bending planes simultaneously (horizontal and vertical planes in the axial direction of the fiber) [50].

Figure 2.1. (a) Microscope photograph of the cleaved facet of the FCF; (b), (c), (d) Reflections spectra of the unstrained FBGs in cores 1, 2, and 3, respectively [50].

Furthermore, shape sensors which can monitor distributed bending and bending direction have also been demonstrated by utilizing FBGs inscribed in tri-core [51], four-core [52-54] and seven-core fibers [55]. In [51], a research group from NASA reported a shape sensor based on FBGs written in a tri-core fiber. The tri-core fiber had a symmetrical structure, the core distance, cladding diameter, and coating diameter were $68\text{ }\mu\text{m}$, $330\text{ }\mu\text{m}$, and $510\text{ }\mu\text{m}$, respectively. The FBGs located in each core with intervals of 10 mm along the fiber. The experimental results still showed an error of 7.2% . In [52], a twisted four-core fiber was designed and fabricated for simultaneous measurement of bending and twist. A permanent twist bias was induced into the fiber during the fiber drawing. Fig. 2.2 depicts the schematic diagram of the FCF-based sensor. The three twisted outer cores were widely spaced in azimuthal angle for

unambiguous bend monitoring. As the FBG in the straight center core is insensitive to bending or twist variation if it locates at the centerline of the fiber, the FBG in the center core can be utilized as the reference for temperature or axial strain change. The twist measuring accuracy was limited 25 degrees/meter. The present accuracy level was too low for practical applications. In [53, 54], multipoint curvature shape sensors were reported based on FBGs arrays inscribed in each core of a non-twisted homogenous FCF, the schematic view of the sensors was shown in Fig. 2.3. The four identical cores located at the corners of a square lattice with a side length of $36\text{ }\mu\text{m}$. All the cores were designed for single mode operation. The curvature magnitude and direction can be obtained simultaneously. In [55], P. S. Westbrook *et al.* demonstrated an optical shape sensor module based on continuous weak FBGs fabricated in a twisted seven-core fiber. The cladding diameter and core-to-core distance of the seven-core fiber were $125\text{ }\mu\text{m}$ and $35\text{ }\mu\text{m}$, respectively. To ensure the strength, the fiber was coated by a UV transparent layer. The FBGs was inscribed with the standard scanned phase mask method.

Figure 2.2. Bending and twist sensor based on four-core fiber [52].

Figure 2.3. Schematic diagram of the multipoint curvature sensor. (a) A general view of the multi-point curvature sensor. (b) A segment of the bent optical fiber with one group FBGs, F is defined as the external force. (c) Cross-sectional view of the optical fiber, where r , d_o , and θ_d represents the radius of curvature, the distance from the origin of the neutral axis to the center of the cores, and the direction of curvature, respectively [54].

Figure 2.4. Schematic diagram of a fan-out device connecting seven SSMF to a seven-core fiber [55].

It is worth noting that simultaneous interrogation of the multiple cores demands high precision and cumbersome alignment with a coupler and a ball lens [48] or fan-out devices [54, 56]. In most cases, fan-out devices are utilized to couple the light into different cores of weakly coupled MCFs. However, the fabrication of fan-out devices is relatively complicated, and they will increase the cost. Figure 2.4 shows a fan-out device which is designed for connecting seven single mode fibers (SSMFs) to a seven-core fiber.

2.2 LPFGs in MCFs

LPFGs are transmission gratings, no light can be reflected from LPFGs. In an LPFG, the light coupling occurs between the modes propagating in the same direction. As the modes propagate in the same direction, thus $\beta_2 > 0$, according to Eq. (2.1), the resonant wavelengths of an LPFG can be described by [36, 41, 57]:

$$\lambda_i = (n_{eff,core} - n_{eff,i})\Lambda \quad (2.10)$$

where $n_{eff,core}$ is the effective refractive index of the core mode, and $n_{eff,i}$ represents the effective refractive index of the i -th order cladding mode. By comparing Eq. (2.2) and Eq. (2.10), we can find that for a certain resonant wavelength, an LPFG will have a much larger grating period than an FBG.

2.2.1 Sensing principles of LPFGs

LPFGs can respond to a few of parameters such as temperature T , strain ε , and curvature C , these parameter variations will result in wavelength shifts of the resonant wavelengths, which can be expressed as [58]

$$\Delta\lambda = S_T\Delta T + S_\varepsilon\Delta\varepsilon + S_C\Delta C \quad (2.11)$$

where ΔT , $\Delta\varepsilon$ and ΔC are temperature variation, strain variation, and curvature variation, respectively. S_T , S_ε and S_C represent the sensitivities to temperature, strain, and curvature, respectively. The sensitivities can be described as $S_\xi = \partial\lambda/\partial\xi$, where ξ represents T , ε , or C . According to Eq. (2.3), the sensitivities can be rewritten as [58]

$$S_\xi = \left[\Lambda \frac{\partial(n_{eff,core} - n_{eff,i})}{\partial\xi} + (n_{eff,core} - n_{eff,i}) \frac{\partial\Lambda}{\partial\xi} \right] \quad (2.12)$$

In Eq. (2.12), the first term corresponds to the changes of the propagating modes and their effective refractive indices caused by the environmental factors, i.e. the applied parameters, and the second term corresponds to the grating period variations.

After obtaining the sensitivities of an LPFG by calibration, the temperature variation, applied strain, and curvature can be calculated respectively according to Eq. (2.11) by monitoring the wavelength shift of an LPFG.

2.2.2 Sensing applications of LPFGs in MCFs

It is well known that the resonant dips of LPFGs can be affected by several physical parameters, such as temperature, strain, refractive index, thus the cross-sensitivity is an issue needed to be considered for LPFG sensing applications. Thanks to the SDM advantages of LPFGs in MCFs, multiparameter sensing without cross-sensitivities can be realized. In 2017, Ruoxu Wang *et al.* fabricated spatially arrayed LPFGs in a heterogeneous seven-core fiber based on electrical arc discharge mechanism. By using a pair of fan-in/fan-out devices, different transmission spectra of seven LPFGs in the seven cores were obtained. Thanks to the low negligible crosstalk between the center core and the outer core, LPFGs fabricated in the seven cores were highly independent and could act as independent sensing units. By monitoring the wavelength shifts of the LPFGs in the center core and one outer core, and constructing a matrix consisting of the temperature and strain sensitivities, simultaneous measurement of temperature and strain has been demonstrated [59]. In 2017, David. Barrera *et al.* proposed a selective LPFG inscription technique and demonstrated a directional bending sensor based on LPFGs inscribed in a seven-core fiber [60]. The LPFGs were selectively fabricated into the center core and two outer cores which were in the same planes, as shown in Fig. 2.5(a). After three times of LPFGs fabrication, the center core contained three LPFGs with different resonant wavelengths, and each outer core only had one particular LPFG, as shown in Fig. 2.5(b). The LPFGs in the outer cores showed linear curvature sensitivities whereas the LPFGs in the center cores exhibited negligible curvature sensitivities. The sensor exhibited the ability of curvature sensing for a curvature range from 0 m^{-1} to 1.77 m^{-1} and bending directions from 0° to 360° , the maximum curvature sensitivity was 4.85 nm/ m^{-1} .

Figure 2.5. (a) Schematic diagram of the MCF cross-section and the defined planes for LPFG inscriptions. (b) The scheme of the LPFGs fabricated in the seven cores [60].

2.3 MZIs in MCFs

2.3.1 Sensing principles of MZIs

MZIs have widely used in diverse optical fiber sensing applications due to their flexible configurations. A basic MZI has two arms, as shown in Fig. 2.6, I_{in} represents the intensity of an input signal in the lead-in fiber, which is split into two arms by coupler 1. The intensities of the signal in the two arms are I_1 and I_2 , respectively. After propagating through the two arms, the light is recombined into a lead-out fiber by coupler 2. Because of the optical path difference (OPD) between the two arms, the recombined light will generate interference. For sensing applications, one arm is used as a reference which is isolated from external perturbation. As the sensing arm, the other arm will be affected by the sensing parameters such as strain, temperature, and bending. Any perturbation of the sensing arm will result in OPD variation and then changes the interference signal. The intensity of the output interference signal can be described as [61]:

$$I_{out} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\phi_{MZI}) \quad (2.13)$$

where ϕ_{MZI} represents the accumulated phase difference caused by the OPD, it can be obtained from

$$\phi_{MZI} = \frac{2\pi}{\lambda}(n_1L_1 - n_2L_2) \quad (2.14)$$

where n_1 and n_2 , L_1 and L_2 denote the refractive indices, and the lengths of the two arms, respectively.

Figure 2.6. Schematic of a basic MZI. An input beam is split into two arms by coupler 1, and then recombined together by coupler 2.

The scheme of using two separate arms to form an MZI has some drawbacks, for example, it is difficult to keep the reference arm unaffected by environment. To replace the basic scheme, various optical fiber in-line MZIs have been demonstrated [62]. For in-line MZIs, the reference and sensing arms are in the same fiber and have the equal physical length, but still have OPD due to the modal dispersion, and Eq. (2.14) can be rewritten as:

$$\phi_{MZI} = \frac{2\pi}{\lambda} \Delta n_{eff} L_{MZI} \quad (2.15)$$

where Δn_{eff} is the effective refractive index difference between the two interference modes, L_{MZI} denotes the interaction length. When $\phi_{MZI} = (2m+1)\pi$, ($m = 0, 1, 2, \dots$), the intensity of the interference pattern will have a minimum value at the wavelengths [63]

$$\lambda_{m,MZI} = \frac{2\Delta n_{eff} L_{MZI}}{2m+1} \quad (2.16)$$

Variations of temperature, strain or other physical parameters applied on the MZI will change the refractive indices or the physical length, according to Eq. (2.16), the resonant wavelengths will shift.

2.3.2 Sensing applications of MZIs in MCFs

In recent years, many schemes of MZIs based on MCFs have been demonstrated for sensing applications. These schemes can be roughly divided into two categories. The first one is fabricating an MZI by just splicing a segment of MCF automatically between two SMFs without lateral offset by using a fusion splicer. The second category is making an MZI by splicing a section of MCF between two SMFs with a lateral offset, or splicing a section of MCF between two MMFs and then connected to two SMFs, or tapering the MCF.

The MZIs of the first category have been demonstrated based on a twin-core fiber (TCF) [64], FCF [65], or strongly coupled seven-core fiber [66-69]. Figure 2.7 shows the microscope images of a TCF, FCF and strongly coupled seven-core fiber which have been used for forming the first category of MZIs. In 2009, Suchun Feng *et al.* reported a compact in-fiber MZI based on a TCF spliced two SMFs for temperature and strain sensing. The temperature and strain sensitivities of the sensor were about 0.037 nm/°C and 0.866 pm/μ ϵ , respectively [64]. In 2016, Chao Li *et al.* demonstrated an MZI based on a FCF spliced two SMFs, the responses to strain, curvature and refractive index of the sensor have been investigated. The experimental results showed that the strain, curvature, and refractive index sensitivities were 2.21 pm/μ ϵ , 2.55 nm/m⁻¹ and 113.27 nm/RIU, respectively [65]. A few reports about MZI sensors based on strongly coupled seven-core fiber have been demonstrated for sensing force and temperature [66], high-temperature [67], curvature [68] and accurate vibration [69].

Figure 2.7. Microscope images of the MCFs spliced directly between two SMFs, (a) twin-core fiber [64], (b) four-core fiber [65], (c) strongly coupled seven-core fiber [66].

For the second category of MCF based MZIs, usually, to couple light into all the cores, the methods of splicing the MCF and SMF with lateral offset, splicing a segment of MMF between the MCF and SMF, or tapering the MCF were used. In 2013, Zhiyong Zhao *et al.* demonstrated a seven-core fiber-based multipath MZI by offset splicing the MCF between two SMFs for temperature sensing [70], the schematic diagram of the sensor structure and the cross-sectional microscope image of MCF, are shown in Fig. 2.8 (a) and Fig. 2.8(b), respectively. The obtained highest temperature sensitivity of the sensor was 130.06 pm/°C, and the strain sensitivity was less than 0.284 pm/με. In 2016, Lin Gan *et al.* proposed and demonstrated spatial-division MZIs by tapering an MCF for simultaneous measurement of strain and temperature. The structure of the MZI and the cross-sectional image of the MCF are illustrated in Fig. 2.8 (c) and Fig. 2.8(d), respectively. By using a pair of fan-in/fan-out devices, seven channels of MZIs can be interrogated independently. The MZI in the center core showed a temperature sensitivity of 47.73 pm/°C, and a strain sensitivity of 1.10 pm/με. The MZI in the outer core exhibited a temperature sensitivity of 53.20 pm/°C, and a strain sensitivity of 0.84 pm/με. Multiparameter sensing can be realized by parallel monitoring MZIs in different cores [71]. In 2017, Xiaoliang Wang *et al.* fabricated an MCF-based MZI for temperature and curvature sensing. The MZI was fabricated by splicing a segment of MCF between two short MMFs and then connecting two SMFs. One MMF was used to couple the light to the cladding and all the cores of the MCF, the other one was used to couple the light back to the lead out SMF. Figure 2.8 (e) and Figure 2.8 (f) show the schematic diagram of the MZI structure and the cross-sectional image of the corresponding MCF, respectively. The sensor showed a temperature sensitivity of 55.81 pm/°C and a very high curvature sensitivity of 31.54 nm/m⁻¹.

Figure 2.8. Schematic diagrams of the MCF-based MZI structures and the cross-sectional images of the MCFs. (a) MZI was formed by offset splicing the MCF between two SMFs [70]. (c) MZI was based on a tapered MCF [71]. (e) MZI was formed by splicing the MCF between two MMFs then connecting to two SMFs [72]. (b), (d) and (f) show the cross-sectional microscope images of the MCFs used in the three types of MZIs [70-72], respectively.

2.4 MIs in MCFs

2.4.1 Sensing principles of MIs

Optical fiber sensors based on MIs have similar structures with the sensors based on MZIs. The difference between MIs and MZIs is that an MI only need one fiber structure such as an LPFG or a tapered region as the splitter and combiner. In addition, MZIs

work in the transmission direction, whereas MIs work in reflection direction which makes MIs suitable to act as probe sensors. The fundamental working principle is based on the interference between the light beams reflected from the mirrors at the end of two arms, as shown in Fig. 2.9 (a). MIs can have more compact size and are more convenient for practical applications than MZIs [73]. The two independent arms of the basic MI are easily affected by different perturbations, which will result in sensing errors. Thus, in-line MIs have been attracted more attention than the basic MIs, especially for monitoring temperature and the refractive index of liquids. Figure 2.9(b) illustrates the schematic diagram of an in-line MI, in which the light is coupled to the cladding and the core and reflected back by the mirror at the end face.

Figure 2.9. (a) Schematic diagram of the basic configuration of an MI. (b) Schematic diagram of an in-line fiber MI [62].

Since the light propagates twice along the two arms in an MI, according to Eq. (2.15), the accumulated phase difference between the two interference modes of an MI can be described by:

$$\phi_{MI} = \frac{4\pi}{\lambda} \Delta n_{eff} L_{MI} \quad (2.17)$$

where L_{MI} represents the physical length. When temperature, strain, or other external stimuli change, the refractive index or the fiber length will also be affected, which will result in wavelengths shift of the resonant dips. Thus, by monitoring the resonant dips, sensors based on MIs can be realized.

2.4.2 Sensing applications of MIs in MCFs

To date, both weakly-coupled MCFs and strongly-coupled MCFs have been demonstrated for implementing MIs. In 2016, Li Duan *et al.* proposed and demonstrated a compact high temperature sensor based on an MI consisting of a lead-in/lead-out SMF and a segment of a weakly-coupled MCF. The MI was fabricated by tapering the splicing region between an SMF and an MCF, and then the end face of the MCF was made into a spherical reflective mirror by arc-fusion splicing. The structure of the MI and the cross-sectional image of the MCF are illustrated in Fig. 2.10(a) and Fig. 2.10(b), respectively [74]. The tapered region acted as the first coupler, the light was coupled into all the seven cores and the cladding, and then reflected at the spherical mirror. Thanks to the multipath interferences, the sensor exhibited an enhanced temperature sensitivity of 165 pm/°C up to 900°C. In 2017, Joel Villatoro *et al.* demonstrated an accurate strain sensor and a vibration sensor based on MIs in a type of strongly-coupled MCFs [75, 76]. The schematic diagram of the accurate strain sensor and the cross-sectional image of the strongly-coupled MCF are shown in Fig. 2.10 (c) and Fig. 2.10 (d), respectively. Due to the axial symmetry of the MI structure, only two supermodes can be excited in the MCF when the light propagated from the SMF to the MCF [75, 76]. The two supermodes formed interference and reflected by the mirror at the end of the SMF, as shown in Fig. 2.10(c). The sensor with 14.9 cm of the MCF showed a strain sensitivity of 1.7 pm/με, which was about 40% higher than that of conventional FBGs [77]. The vibration sensor was also based on the similar strongly coupled MCF. Its structure is illustrated in Fig. 2.10 (e). The MCF was spliced to an SMF, and the end face of the MCF acted as a mirror. Then a segment of a capillary tube (CT) was spliced to the MCF to protect the MCF end. The resonance frequency of this vibration sensor can be tuned from a few Hz to several kHz [76].

Figure 2.10. (a) Schematic diagram of the MI based on the weakly-coupled MCF for high temperature sensing [74]. (b) Cross-sectional image of the weakly-coupled MCF [74]. (c) Schematic diagram of the MI based on a strongly-coupled MCF for accurate strain sensing. The MCF was spliced between two SMFs, one of the SMFs has a mirror at the end [75]. (d) Cross-sectional image of the strongly-coupled MCF [75]. (e) Schematic diagram of the MI based on the strongly coupled MCF for vibration sensing [76].

2.5 FPIs in MCFs

2.5.1 Sensing principles of FPIs

An FPI is generally constituted of two parallel reflective surfaces with a certain distance between them [62]. The interference happens due to the multiple superpositions of the reflected or transmitted light at the two mirrors. Optical fiber-based FPIs can generally be divided into two groups, one is extrinsic FPI (EFPI), the other one is intrinsic FPI (IFPI) [78]. In EFPIs, the light can exit the fiber and propagate in an external cavity, the interference is formed by the light reflected from an external cavity. IFPIs can also be referred to as in-line FPIs or in-fiber FPIs [79], in which the reflecting interfaces

locate in the fibers, and the light is confined within the fibers [62, 78]. Figure 2.11 (a) and Figure 2.11 (b) illustrate the schematic diagram of an EPFI and IFPI, respectively. Most of the optical fiber-based FPIs work in the reflection mode which is more convenient in practical applications

Figure 2.11. (a) Schematic diagram of an EFPI formed by an external air cavity, usually the cavity-supporting structure is a capillary tube [62]. (b) Schematic diagram of an IFPI, the two mirrors located inside the fiber [62].

If the reflectivities of the mirrors are very low, for example, silica-air interfaces act as the mirrors, although multiple reflections and transmissions occur at the silica-air interfaces, the multiple-beam interference model of the electric fields of FPIs can be simplified as a two-beam interference by using the two-beam approximation [80]. The reflection or transmission interference is mainly caused by the accumulated phase difference between the two beams reflected at the two mirrors. The accumulated phase difference can be described as:

$$\phi_{FPI} = \frac{4\pi}{\lambda} n_{FPI} L_{FPI}, \quad (2.18)$$

where n_{FPI} and L_{FPI} denote the refractive index and physical length of the cavity, respectively. λ represent the working wavelength. When the phase difference satisfies the condition $\phi_{FPI} = (2m+1)\pi$, ($m = 0, 1, 2, \dots$), the interference resonant dips locate at [81, 82]

$$\lambda_{m,FPI} = \frac{4n_{FPI}L_{FPI}}{2m+1}. \quad (2.19)$$

When the external perturbation is applied to the FPI, the OPD variation of the interferometer will be changed which will result in wavelength shifts of the resonant dips. For instance, external strain applied on to the FPI can change the physical length

of the cavity and/or the refractive index of the cavity material. As a result, the wavelengths of the dips will shift. Thus, the applied strain can be measured by monitoring the wavelength shifts of the dips.

2.5.2 Sensing applications of FPIs in MCFs

In 2016, Yaxun Zhang *et al.* proposed and demonstrated a Michelson Fabry-Perot hybrid interferometer sensor based on a TCF and a silica capillary [83]. The schematic diagram of the hybrid interferometer is shown in Fig. 2.12(a). The MI was formed by taper splicing one end of the TCF to an SMF, and the FPI cavity was formed by splicing a segment of the capillary between the TCF and an SMF. The sensor had the ability of simultaneous measurement of radial bending and axial strain. Moreover, the temperature cross-sensitivity can be compensated automatically.

Figure 2.12. (a) Schematic diagram of the Michelson Fabry-Perot hybrid interferometer sensor [83]. (b) Microscope photograph of the cross-section of the TCF [83]. (c) Microscope photograph of the FP cavity based on the silica capillary [83].

The large size and complexity of the hybrid interferometer reported in [83] limited the potential applications of the sensor. In 2017, Yang Ouyang *et al.* proposed and demonstrated a simpler sensor for directional bending and strain sensing based on spatially arrayed dual air-cavity FPIs, which were fabricated by splicing a dual side-hole fiber between a seven-core fiber and an SMF, as shown in Fig. 2.13(a) [84]. The two FPIs were parallel and mutually independent, which could implement simultaneous measurement of directional bending and axial strain. The cross-sensitivity between the bending and strain could be avoided. The bending sensitivities

of the two FPIs were highly dependent on the bending direction. As shown in Fig. 2.13(a), when the bending direction was 0° , FPI1 and FPI2 exhibited bending sensitivities of 120.5 pm/m^{-1} and -122 pm/m^{-1} , when the bending direction was 180° , FPI1 and FPI2 exhibited bending sensitivities of -121.1 pm/m^{-1} and 110.4 pm/m^{-1} , respectively. The strain sensitivities of the two FPIs were $1.59 \text{ pm}/\mu\epsilon$ and $1.52 \text{ pm}/\mu\epsilon$, respectively.

Figure 2.13. (a) Schematic diagram of the spatially arrayed dual air-cavity FPIs. Cross-sectional microscope images of (b) the seven-core fiber and (c) the dual side-hole fiber. (d) Microscope image of the sensor [84].

2.6 Summary

In this chapter, optical fiber sensors based on MCFs have been reviewed. To date, many schemes of implementing MCF-based sensors have been demonstrated, such as inscribing FBGs or LPFGs in MCFs, fabricating MZIs, MIs or FPIs based on MCFs. The sensing principles of these schemes and the developments of the corresponding types of sensors have been introduced.

Chapter 3 FBGs in Heterogeneous MCF for Directional Bending Sensing

Typically, one key technical challenge for inscribing uniform FBGs in a homogenous weakly-coupled MCF by using a UV laser is the lens effect caused by the fiber cladding. In this chapter, the previously reported methods to improve the uniformity of FBGs in a homogeneous MCF will be reviewed. These methods can make the uniformity a little better, but the non-uniformity still cannot be eliminated. On the contrary, fabricating FBGs in heterogeneous weakly-coupled MCFs with distinctly different Bragg wavelengths is an alternative way to avoid the challenge. The fabrication of FBGs in a trench-assisted heterogeneous seven-core fiber will be presented. This seven-core fiber has six identical outer cores and one center core. The refractive indices of the six outer core is a little larger than that of the center core. Two apparently different Bragg reflection peaks are obtained due to the slight difference of refractive indices between the center core and the outer cores. The sensing performances of the two FBGs will be characterized [85].

3.1 Background and literature review

In the past few years, MCFs have attracted extensive interests for various applications, including high-capacity optical communications, fiber lasers, sensing, etc. This is mainly due to the intrinsic advantages of MCFs, such as well-defined core separation, improved isothermal behaviour, small size, light weight, repeatability, immunity to electromagnetic interference, etc. By inscribing FBGs, MCF-based sensors exhibit great potentials for directional bending sensing applications. Several kinds of bending sensors based on FBGs in homogeneous MCF have been proposed so far. For instance, in 2000, M. J. Gander *et al.* demonstrated a single-axis bending sensor by utilizing FBGs in two cores of an FCF [48]. Subsequently, in 2003, G. M. H. Flockhart *et al.* reported a two-axis bending sensor based on FBGs in three cores of an FCF [50].

Furthermore, three-axis shape sensors which can monitor distributed bending have also been demonstrated by utilizing FBGs inscribed in MCFs [51-55]. However, simultaneous interrogation of the multiple cores demands high precision and cumbersome alignment with a coupler and a ball lens [48], or fan-out devices [50, 51, 53, 55]. To fabricate FBGs in an MCF, the MCF can be exposed to a set of UV fringes which are generated by the interferometric technique or scanned phase mask method. For inscribing FBGs simultaneously into homogeneous MCFs with lateral UV exposure, one of the key challenges is the uneven UV exposure which is caused by the lens effect of the fiber cladding. As shown in Fig. 3.1, when the UV light is incident to the MCF laterally, the cross-section of the fiber will act as a lens which will focus the incident UV light [86]. As a result, the intensity distribution of the UV light is nonuniform at different cores, which result in different UV-induced refractive index modulations in different cores. Consequently, each core will have a different transmission/reflection profile, and the FBGs' performance of eliminating selectively and strongly given narrow bands, for example, the OH emission lines [87], is undermined [88, 89].

Figure 3.1. Schematic diagram of the lens effect of the fiber cladding for a four-core fiber [86].

In order to improve the uniformity of the FBGs in different cores of MCFs, two options have been reported. The first one is to tailor the positions and compositions of the cores [86]. In 2007, by using this method, C. G. Askins *et al.* significantly improved the reflectivity uniformity of the FBGs inscribed in four cores of an MCF by altering the photo-sensitivities and asymmetrical distributions of the cores in the MCF.

However, obvious differences of the Bragg wavelengths of the four FBGs still existed [86]. The second option is to modify the incident field so that the intensity distribution uniformity of the UV light can be improved. In 2012, P. S. Westbrook *et al* demonstrated parallel fabrication of distributed feedback (DFB) laser based on FBGs in a seven-core fiber. For the FBGs fabrication, in order to improve the uniform irradiation of all the cores, they adjusted the transverse dimension of the UV laser beam to about 370 μm which was relatively larger than the fiber diameter. Figure 3.2(a) shows the cross-section of the MCF. Ray tracing of the UV inscription beam applied on the MCF is shown in Figure 3.2(b). As can be seen from Fig. 3.2(b), even though core 2 and core 3 located directly behind of core 6 and core 5 in the direction of the UV light propagation, respectively, all the cores can be irradiated because of the lens effect of the fiber. Figure 3.2(c) illustrates the transmission spectra of the seven FBGs inscribed in the seven cores, as can be seen, the transmission windows of the FBGs in different cores still vary largely from each other [90].

Figure 3.2. (a) Microscope image of the cross-section of an MCF and the incident direction of the UV light beam. (b) Schematic diagram of ray tracing of the UV inscribing beam showing on the MCF. (c) Transmission spectra of the FBGs inscribed in each core measured. Zero wavelength offset corresponds to 1545.762 nm [90].

In 2014, E. Lindley *et al.* proposed to utilize a side-polished capillary covering the MCF to mitigate the lens effect for fabricating uniform FBGs in a seven-core fiber [89]. The cladding diameter of the seven-core fiber and the inner diameter of the tapered side-polished capillary was 125 μm and 140 μm , respectively. Figure 3.3(a) and Fig. 3.3(b) show the cross-sectional microscope images of the MCF and the polished capillary, respectively. The transmission spectra of the seven cores written FBGs without covering the side-polished capillary is shown in Fig. 3.3(c). As can be seen, the wavelengths reflected by the FBGs vary obviously from each other. The uniformity of the transmission spectra of the FBGs become much better when the MCF was covered by the side-polished capillary during the FBG fabrication process, as shown in Fig. 3.3(d). However, there are still differences between the reflected wavelengths [89].

Figure 3.3. (a) Microscope image of the cross-section of the seven-core fiber. (b) Microscope image of the polished capillary tapered to an inner diameter of 140 μm . (c) Transmission spectra of the seven cores with FBGs written without the polished capillary. The inset is the diagram of core numbering. (d) Transmission spectra of the seven cores with FBGs written with the polished capillary [89].

Figure 3.4. Reflection spectra of the FBGs inscribed in an FCF [53].

Furthermore, in order to reduce the influence of lens effect on the simultaneous FBGs inscription in all cores, the UV light beam can be defocused before it passes through the phase mask [53]. Figure 3.4 shows the reflection spectra of the FBGs inscribed in a homogeneous FCF. We can see that the four reflection peaks still differ obviously from each other.

From the aforementioned methods for improving the uniformity of the FBGs in different cores, we can see that even though the results become a little better, but all the complicated schemes still cannot eliminate the non-uniformity. Alternatively, to avoid the challenge of fabricating FBGs in MCFs, another approach is not to improve the uniformity, but to increase the difference of the Bragg wavelengths. This goal can be realized by fabricating FBGs in heterogeneous MCFs. However, there is very little work reported on it, to the best of our knowledge.

In our work, FBGs were fabricated in a trench-assisted all-solid heterogeneous MCF. Differing from the homogeneous MCFs we previously fabricated [91-93] the MCF used in this work has six identical outer cores and a center core with a little lower refractive index. Due to this difference, the reflection peak of the FBG in the center core is separated from that in the outer cores. Thus, the reflections from the center core and the outer cores can be simultaneously detected by only inserting a segment of MMF between the MCF and the lead-in SMF. The bending response of the two FBGs was

analyzed in detail. Moreover, the temperature and strain responses were also investigated. Compared with the previous bending sensors based on FBGs in homogeneous MCFs [48, 50, 51, 53, 55], the present sensor has a much simpler interrogation method. In addition, there is no need to consider the uneven UV exposure, which is usually a bothersome issue for FBGs fabrication in homogeneous MCFs [86, 89].

3.2 Sensor design and fabrication

Figure 3.5(a) shows the microscope image of the cross-section of the MCF used in our experiment. The index profiles of the outer cores and the center core are illustrated in Fig. 3.5(b) and Fig. 3.5(c), respectively. The six outer cores have the same refractive index which is slightly higher than that of the center core. Comparing with the refractive index of the cladding (pure silica), the refractive index differences Δ_1 , Δ_2 , Δ_3 , Δ_4 at 670 nm were measured to be about 0.0053, -0.0038, 0.0047, -0.0006, respectively. The materials of the regions with refractive indices higher than that of the cladding and the index-depressed trenches are germanium-doped silica and fluoride-doped silica, respectively. The core diameter, overall fiber cladding diameter, and the distance d between adjacent cores are about 8.4 μm , 125 μm and 42 μm , respectively. All the seven cores were designed for single mode operation. The large core-to-core distance and trenches ensure mode isolation between the adjacent cores [85].

Figure 3.5. (a) Microscope image of the cross-section of the MCF. Refractive index profiles of the (b) outer core and (c) center core.

Figure 3.6. Effective refractive index curves of the center core mode and outer core mode.

According to the Sellmeier equation, the refractive index of pure silica can be calculated by the following equation [94]:

$$n(\lambda) = \sqrt{1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.8974794\lambda^2}{\lambda^2 - 9.896161^2}} \quad (3.1)$$

It is worth noting that the unit of wavelength in Eq. (3.1) is μm . For germanium-doped silica or fluoride-doped silica, the refractive index can be approximately calculated by adding an offset (refractive index difference) to Eq. (3.1) [95].

The supported center core mode and outer core mode of the MCF were simulated by using COMSOL Multiphysics 5.0. The calculated effective refractive indices of the two core modes were obtained for the wavelength range from 1540 nm to 1620 nm, as depicted in Fig. 3.6. According to Eq. (2.2), the relationship between the FBG resonant wavelength λ_B and the grating pitch Λ can be described by $\Lambda = \lambda_B / (2n_{\text{eff},\text{core}})$, where $n_{\text{eff},\text{core}}$ represents the effective refractive index of the corresponding core mode. Based on the calculated effective refractive indices, the relationships between the grating pitches and the resonant wavelength are derived and plotted in Fig. 3.7(a), and a zoom over the wavelength range from 1599 nm to 1601 nm is illustrated in the inset. For a given grating pitch, e.g. 553.56 nm, the Bragg wavelength in the outer core is a little larger than that of the center core, as shown in the inset of Fig. 3.7(a). The dependence

of the wavelength spacing between the Bragg wavelengths of the center core and that of the outer cores on the grating pitch can be calculated according to the expression $\Delta\lambda_B = 2\Delta n_{eff,core}\Lambda$, where $\Delta n_{eff,core}$ represents the effective refractive index difference of the two type of core modes, the result is plotted in Fig. 3.7(b). When the grating pitch is 553.56 nm, the theoretical Bragg resonant wavelengths of the center core and outers are 1599.98 nm and 1600.53 nm, respectively. The wavelength spacing of the two Bragg resonant wavelengths is about 0.554 nm, which is large enough to avoid overlap between the center core FBG and outer core FBG. Thus the reflected signal of the two FBGs can be simultaneously detected by only splicing a segment of MMF between the MCF and SMF

Figure 3.7. (a) Calculated grating pitches against Bragg resonant wavelength for the center core and outer cores. The inset shows a zoom over the wavelength range from 1599 nm to 1601 nm. (b) Calculated wavelength spacing between the Bragg resonant wavelengths of the center core and that of the outer cores against the grating pitch.

Figure 3.8. Schematic diagram of the proposed direction bending sensor.

Figure 3.9. Schematic diagram of the scanned phase mask method for FBG fabrication.

The configuration of the proposed directional bending sensor is illustrated in Fig. 3.8. Only one outer core and the center core were utilized. The MMF acted as a coupler to couple the light into the center core and outer core, and recouple the reflected signal to the lead-in SMF. The other five outer cores provide added flexibility in manufacturing [55]. The sensor was fabricated by two main steps: FBGs fabrication and core-offset splicing. The FBGs in this heterogeneous MCF were inscribed with the scanned phase mask method.

Figure 3.9 illustrates the schematic diagram of the FBG fabrication system, which consists of a linear scanning stage supporting the mounts of a mirror and a cylindrical lens. The cylindrical lens is utilized to concentrate the laser in the inscribing area of the fiber. The fiber should be fixed straightly in close proximity behind the phase mask with a distance at few micrometers level [37], and the direction of the fiber should be kept perpendicular to the fringes of the phase mask. When the incident UV laser passes through the cylindrical lens diffraction occurs and interference is generated by the plus

one and minus one orders of the diffraction [96]. During the grating fabrication process, the UV interference pattern induces a refractive index modulation into the core of the photosensitive fiber. The period of the index modulation (the pitch Λ of the grating) equals to half of the pitch Λ_{pm} of the phase mask, i.e., $\Lambda = \Lambda_{pm} / 2$ [97].

Figure 3.10. Transmission (blue) and reflection (red) spectra when the MCF was spliced between two SMFs without lateral offset.

Here, the pitch of the phase mask is $\Lambda_{pm} = 1107.12$ nm, thus the pitch of the corresponding FBG is $\Lambda = 553.56$ nm. Prior to the FBGs inscription, the MCF was photosensitized via hydrogen loading at 12 MPa at 80 °C for 9 days. For monitoring the inscription process, a segment of the hydrogen-loaded MCF was spliced between two SMFs by matching their cores to the MCF's center core. Then, it was connected to a broadband light source (BLS) (Infinon Research) and an optical spectrum analyzer (OSA) (YOKOGAWA, AQ6370C). A 244 nm frequency-doubled Argon laser with the power of 95 mW was used as the UV light source. Since all the cores were made of germanium-doped silica, the FBGs in these cores could be inscribed simultaneously. The scanning speed and inscription length were 0.035 mm/s and 14 mm, respectively. After inscription, the MCF with FBGs was annealed in a chamber at 100 °C for 24 hours to stabilize the FBG wavelengths. The transmission and reflection spectra of the center core are shown in Fig. 3.10. There are only one obvious notch and peak that can be found in the transmission and reflection spectra, respectively. Since the MCF was

spliced to SMFs without any core offset, this reflected peak located at around 1599.75 nm should come from the FBG in the center core.

After the FBG fabrication, the MCF was cleaved at both ends. In order to simultaneously couple the Bragg reflections of the outer core and the center core back to the core of the lead-in SMF, a segment of MMF was spliced between the SMF and MCF. The MMF with the length of about 1 mm was spliced to the lead-in SMF without a lateral offset. The core diameter and cladding diameter of the MMF were 105 μm and 125 μm , respectively. During the process of splicing the MCF to the MMF, the near-field image at the output facet of the MCF was monitored by using a beam view system with a microscope objective lens, a CCD camera (COHENREN, E-7290) , and a laser (ANDO, AQ4321D) at 1580 nm, as shown in Fig. 3.11. In order to avoid splitting or broadening of the Bragg reflections when the MCF is bent, only one outer core and the center core are desired to reflect the light. By trial and error, when the MCF was spliced to the MMF with a lateral offset of about 13 μm , the near-field image was recorded as shown in Fig. 3.12. The light was mainly coupled into the center core and one outer core. Then another segment of SMF was spliced to the MCF without a lateral offset. This SMF was utilized for fixing the sensor in the following experiments. The reflection spectrum of the sensor was measured by the OSA with a resolution of 0.02 nm, as shown in Fig. 3.13. The central wavelengths of the two reflection peaks are about 1599.75 nm and 1600.31 nm, respectively, and the wavelength spacing between the two peaks is about 0.56 nm. The measured results of the Bragg wavelengths and wavelength spacing coincide well with the theoretically calculated ones in the fourth paragraph of section 3.2. The shorter wavelength reflection peak in Fig. 3.13 corresponds to the reflection peak of the center core shown in Fig. 3.10. The longer wavelength reflection peak in Fig. 3.13 cannot be attributed to the cladding modes, but to the FBG inscribed in the outer core.

Figure 3.11. Schematic diagram of the beam view system

Figure 3.12. Near-field image at the output facet of the MCF with a lateral offset between the MMF and MCF.

Figure 3.13. Reflection spectrum of the proposed sensor with lateral offset splicing between the MMF and MCF.

3.3 Principle of operation

Figure 3.14(a) shows the schematic diagram of the experimental setup for directional bending sensing. In order to avoid externally applied axial strain during the bending

experiment, the sensor was placed into a capillary which was fixed on the bottom side of a plastic beam, as shown in Fig. 3.14(a) with the red curve. The inner diameter of the capillary is about $252\text{ }\mu\text{m}$. The ends of the fiber were fixed by the clamps of rotator-1 and rotator-2 so that the sensor can be rotated simultaneously without inducing twist during the experiments. Both rotator-1 and rotator-2 can rotate 360° , and the angular accuracy is about 2° . The plastic beam was fixed on the two translation stages. One of the two translation stages was fixed while the other one could be moved back and forth along the z-axis to change the curvature of the sensor. During the process of changing the curvature, the sensor can bend freely and will experience no externally applied axial strain but only bend-induced strain. The bending lies in the vertical plane, i.e., x-z plane. Forward movement of the movable stage can increase the curvature. Light from the BLS was launched into the sensor through an optical circulator (OC), the reflection spectrum was monitored by the OSA.

Figure 3.14. (a) Experimental characterization setup of the proposed curvature sensor. (b) Theoretical definition of the bending orientation angle θ . (c) Schematic diagram of bending when $\theta = 270^\circ$.

Assuming that only one outer core is involved for the proposed curvature sensor. Then the bending orientation angle can be theoretically defined as illustrated in Fig.

3.14(b), where the two dark blue circles represent the center core and the corresponding outer core. The center of curvature locates at the positive direction of x coordinate and the origin point of the coordinate is set at the center of the fiber. Figure 3.14(c) shows the schematic diagram of bending when $\theta = 270^\circ$. When the beam is bent, the bending beam and fiber can be treated approximately as an arc of a circle [98]. Thus all the sensor region nearly has the same curvature. The applied curvature C can be calculated by [99]:

$$\sin\left(\frac{DC}{2}\right) = \frac{(D - \Delta D)C}{2} \quad (3.2)$$

where D is the initial separation between the two fixed ends of the beam without bending, ΔD represents the distance of the movable stage moving forward to the fixed one. In our experiment, D was set as 249.5 mm.

According to Eq. (2.7), when the fiber is bent with a curvature radius R , the z -component (axial component) ε of the bend-induced strain can be described by $\varepsilon = -Cx$. The inner side of the bending fiber ($x > 0$) will be compressed while the outer side ($x < 0$) will be stretched. And the z -component of bend-induced strain along the sensor is the same.

Based on Eq. (2.5), the curvature caused wavelength shift $\Delta\lambda_{B,c}$ of an FBG can be described by [48]:

$$\Delta\lambda_{B,c} = -\lambda_B(p_\varepsilon + 1)Cx \quad (3.3)$$

According to the Eq. (3.3), when the outer FBG locates at the inner side ($x > 0$) of the bent fiber, the FBG wavelength will shift to shorter wavelength side with increasing the curvature. On the contrary, when the outer FBG locates at the outer side ($x < 0$), the FBG wavelength will shift to longer wavelength side with increasing the curvature. As the distance between the outer core and the center core is d , so the central wavelength shift of the investigated outer FBG is approximately determined by $Cd \sin(\theta)$. Therefore, the outer FBG is directionally sensitive to the curvature variation, and a sine function with a period of 360° could be utilized to describe the relationship

between the curvature sensitivity (wavelength shift divided by the curvature variation) of the outer FBG and the bending orientation angle. As the FBG in the centric core is insensitive to curvature [41, 100], it can be utilized for compensating temperature or externally applied axial strain.

3.4 Experimental results and discussion

Since the experimental bending orientation angle θ_e may be deviated from the theoretically defined bending orientation angle θ , a calibration for the bending angle is required. During the calibration, the initial θ_e was first chosen as zero degree. Then, the curvature was increased from 0 to 1.896 m^{-1} step by step and the corresponding reflection spectra were recorded. After completing the data collection, the movable stage was carefully moved back to its original position and then both of the two rotators were rotated by the same angle simultaneously. After the rotation, the reflection spectra were measured again with increasing the curvature as mentioned above. These measurements were repeated for θ_e with different values. Figure 3.15 shows the central wavelength shifts of the center FBG and the outer FBG at fourteen different θ_e . The central wavelength was calculated as the mid-point at the -3 dB threshold of the peak. In accordance with the theoretical prediction [41, 100], no obvious wavelength shift of the center FBG was observed during the whole bending process for all the different θ_e . It can be further demonstrated by the inset of Fig. 3.15 which illustrates the wavelength fluctuations of the center FBG. All the values are less than or equal to 0.02 nm. In contrast, the outer FBG presents negative or positive curvature sensitivity when the corresponding outer core locates at the inner side or the outer side of the bending fiber, respectively. Comparing with the outer FBG, the wavelength shifts of the center FBG are negligible. The outer FBG is insensitive to bending for the curvature range from 0 m^{-1} to 0.176 m^{-1} , which is mainly caused by the resolution limitation (0.02 nm) of the OSA. The wavelength shifts caused by the small curvature are not large enough for the OSA distinguishing them accurately. All the lines in Fig. 3.15 are the linear fitting between the central wavelength of the outer FBG and the curvature from 0.176 to 1.896 m^{-1} for the fourteen different θ_e . The slope (curvature sensitivity), R^2

value of the linear fitting line, and the corresponding θ_e are listed in Table 3.1. As can be seen from Table 3.1, the difference of the bending orientation angles between the two smallest curvature sensitivities (the corresponding θ_e are 60° and 240°) is 180° . Similarly, the difference of the bending orientation angles between the two largest curvature sensitivities (the corresponding θ_e are 150° and 330°) is also 180° . This phenomenon accords with the principle that the curvature sensitivity of the outer FBG varies with respect to the bending orientation angle in the form of a sine function with a period of 360° . We also notice that when θ_e equals to 30° , 60° and 240° , the linearity is relatively poor. It is caused by a small curvature sensitivity and the resolution limitation of the OSA.

Figure 3.15. Central Wavelength shifts versus curvature for the two FBGs at different bending directions. The inset shows the central wavelength fluctuations of the center FBG at different bending directions over the curvature range from 0 to $1.896 m^{-1}$.

Table 3.1. Results of linear fitting between the central wavelength of the outer FBG and curvature for different θ_e

θ_e (°)	Slope (nm/m ⁻¹)	R^2	θ_e (°)	Slope (nm/m ⁻¹)	R^2
0	0.09828	0.998	180	-0.09643	0.997
15	0.07341	0.993	210	-0.05137	0.996
30	0.04393	0.960	240	0.01386	0.958
60	-0.01789	0.974	270	0.07407	0.994
90	-0.08383	0.996	300	0.11943	0.996
120	-0.11899	0.999	330	0.12257	0.998
150	-0.12101	0.999	360	0.09315	0.994

Based on the results in Table 3.1, the relationship between the curvature sensitivity of the outer FBG and the experimental bending orientation angle θ_e was fitted with a sine function, as shown in Fig. 3.16 (a). The obtained fitted equation is given by:

$$S_C = 0.1252 \sin(\theta_e - 231.64^\circ) - 0.0017 \quad (3.4)$$

where S_C represents the curvature sensitivity. For the calibration of the bending orientation angle, $\theta = \theta_e - 231.64^\circ$. According to the theoretical definition of the bending orientation angle shown in Fig. 3.14(b), the corresponding outer FBG and the neutral axis of the fiber locating simultaneously in the bending plane will result in maximum curvature sensitivity. Therefore, the bending sensor should have a maximum curvature sensitivity when $\theta_e = 321.64^\circ$ or $\theta_e = 141.64^\circ$ which should be corresponding to $\theta = 90^\circ$ or $\theta = -90^\circ (270^\circ)$, respectively.

Figure 3.16. (a) Relationship between curvature sensitivity and experimental bending orientation angle θ_e . (b) Central wavelength of the outer FBG versus curvature for $\theta_e = 142^\circ$ and $\theta_e = 322^\circ$. Spectral responses of the FBGs with varying curvature for (c) $\theta_e = 142^\circ$, (d) $\theta_e = 322^\circ$.

Since the proposed experimental setup only has an angular accuracy of about 2° , the spectral responses of the bending sensor to the curvature variation for the maximum curvature sensitivity were measured when θ_e were 142° and 322° . The central wavelength of the outer FBG has a good linear response to curvature variation with the R^2 value of 0.999 for both 142° and 322° . The curvature sensitivities are -0.122 nm/m^{-1} and 0.128 nm/m^{-1} , respectively, as shown in Fig. 3.16(b). The maximum curvature sensitivity is much higher than the previously reported results [48, 50, 101, 102]. As illustrated in Fig. 3.16(c) and Fig. 3.16(d), there is nearly no wavelength shift of the center FBG when the curvature increases for both of the two selected bending orientations. For the outer FBG, the wavelength shifts to shorter wavelength side when $\theta_e = 142^\circ$, whereas it presents red-shift when $\theta_e = 322^\circ$. The main reason for this phenomenon is that when $\theta_e = 142^\circ$, the outer FBG located at the inner side of the bending

fiber, and the FBG experienced a compressive axial component of bend-induced strain. While when $\theta_e = 322^\circ$, the outer FBG located at the outer side of the bending fiber and experienced a tensile axial component of bend-induced strain. No obvious splitting is observed for the reflection peak of the outer FBG when the curvature increases, as shown in Fig. 3.16(c) and Fig. 3.16(d). It indicates that this reflection peak comes from only one outer core rather than multiple cores.

Table 3.2. Curvature sensitivity S_C , measured values λ_1, λ_2 , measured curvature C' , applied curvature C , and the measurement relative error for different θ_e

θ_e ($^\circ$)	S_C (nm/m $^{-1}$)	Measured value		C' (m $^{-1}$)	C (m $^{-1}$)	Relative error ^a (%)
		λ_1 (nm)	λ_2 (nm)			
160	-0.1205	1600.31	1600.22	0.9227	0.8967	2.90
			1600.18	1.2546	1.2562	0.12
190	-0.0849	1600.32	1600.26	0.8825	0.8967	1.58
			1600.23	1.2359	1.2562	1.62
220	-0.0269	1600.33	1600.31	0.9193	0.8967	2.52
			1600.30	1.2910	1.2562	2.77

$$^a \text{Relative error} = |C' - C| / C \times 100\%$$

In order to further evaluate the performance of the proposed bending sensor, we measured the bending response of the sensor again for several other θ_e , i.e., 160° , 190° and 220° . The relative errors of curvature measurement for the three different θ_e were investigated. The applied curvature C and curvature sensitivity S_C for each θ_e can be calculated by Eq. (3.2) and Eq. (3.4), respectively. The measured curvature can be calculated by $C' = (\lambda_2 - \lambda_1) / S + 0.176$, where λ_1 is the central wavelength of the outer FBG for the applied curvature $C = 0.176 \text{ m}^{-1}$, and λ_2 is the central wavelength of the outer FBG after increasing the applied curvature. λ_1 was utilized as the reference wavelength and λ_2 was collected for two different applied curvature values (0.8967 m^{-1} and 1.2562 m^{-1}) for each θ_e , respectively. The three experimental bending orientation angles θ_e ,

curvature sensitivity S_C , measured λ_1 and λ_2 , measured and applied values of curvature, and the relative error of curvature measurement are listed in Table 3.2. As shown in Table 3.2, the relative errors are satisfied with the values within 2.90 %. Larger curvature sensitivities should have smaller relative errors. According to the results shown in Table 3.2, except the relative error in the first row, all other data coincide well with this expectation. The data in the first row, a larger sensitivity has a larger error, it should be caused by the experimental error of the data collection.”

For a curvature sensor, the cross-sensitivity to temperature or externally applied axial strain is an important issue needs to be taken into consideration. The temperature response of the proposed sensor was measured by putting the sensor in the straight groove of an electric controlled oven with temperature precision of 0.1°C without bending. Tuning the temperature from 23 °C to 95 °C, the central wavelength shifts of the center FBG and outer FBG were recorded as shown in Fig. 3.17(a). The temperature sensitivities obtained by linear fitting were about 0.00992 nm/°C ($R^2=0.999$) and 0.00998 nm/°C ($R^2=0.999$), respectively. The two FBGs nearly had the same temperature sensitivities. It's because all the cores were in good thermal contact, thermal gradients between the cores could be neglected. Thus this sensor exhibits good isothermal behavior. It can be used in an environment with uncontrolled temperature.

To investigate the response to the externally applied axial strain of the proposed sensor, the sensor was clamped straightly between two stages with a distance of 245.0 ± 0.1 mm. One stage was fixed, the other one could be moved by a micrometer to stretch the fiber. When the externally applied axial strain increases from 0 to 1102.04 $\mu\epsilon$, the central wavelengths of the two FBGs shift to longer wavelength with the same tendency. In addition, the two FBGs have the same axial strain sensitivity of 1.01 pm/ $\mu\epsilon$, as shown in Fig. 3.17(b). Since the two FBGs experienced the same axial strain, and the difference between the central wavelengths of the two FBGs was very small, thus the two FBGs nearly had the same response to externally applied axial strain.

Figure 3.17. (a) Temperature responses of the central wavelengths of the FBGs. (b) Externally applied axial strain responses of the central wavelengths of the FBGs.

Both of the central wavelengths of the two FBGs can be utilized as two indicators, the curvature sensitivity of the outer FBG for a certain bending orientation can be calculated by Eq. (3.4), and the curvature sensitivity of the center FBG is approximately 0. In addition, the temperature sensitivities and external applied axial strain sensitivities of the two FBGs have been obtained. Therefore, when the curvature sensitivity of the outer core is not equal to zero, by constructing a matrix consisting of the curvature and temperature sensitivities [103] or curvature and externally applied axial strain sensitivities [104], the influences of temperature or externally applied axial strain on directional bending measurement can be eliminated.

3.5 Summary

In conclusion, the methods of improving the uniformity of the FBGs fabricated in MCFs have been reviewed. The nonuniformity of the FBGs is very difficult to eliminate. On the other hand, fabricating FBGs with obviously different Bragg wavelengths in heterogeneous MCFs have several advantages, for instance, it can avoid the technical challenge of FBGs fabrication in homogeneous MCFs, and the FBGs can be interrogated without complicated fan-out devices. We have successfully inscribed FBGs into a trench-assisted all-solid heterogeneous MCF with the scanned phase mask

method. Due to the difference in refractive indices between the center core and outer cores, two FBGs with obviously different central wavelengths were measured by only splicing a segment of MMF between the MCF and the lead-in SMF. Since no complicated and expensive fan-out device was used, the proposed sensor offers several advantages, such as low cost and flexibility in fabrication. The detailed relationship between the curvature sensitivity of the outer FBG and the experimental bending orientation angle was obtained. The maximum curvature sensitivity of 0.128 nm/m^{-1} is much higher than the previously reported results based on eccentric FBG [48, 50, 101, 102]. Moreover, the cross-sensitivity to temperature or externally applied axial strain can be eliminated. With the development of heterogeneous MCFs with three or more different kinds of cores, the scheme of fabricating the proposed sensor is promising for designing shape sensors without using fan-out devices.

Chapter 4 Highly Sensitive Strain Sensor Based on Helical Structure in MCF

Optical fiber sensors for strain measurement have been playing important roles in structural health monitoring for buildings, tunnels, pipelines, aircrafts, and so on. This chapter presents a highly sensitive strain sensor based on an HS assisted MZI in an all-solid heterogeneous MCF. Due to the HS, a maximum strain sensitivity as high as $-61.8 \text{ pm}/\mu\epsilon$ was experimentally achieved. This is the highest sensitivity among interferometer-based strain sensors reported so far, to the best of our knowledge. Moreover, the proposed sensor has the ability to discriminate axial strain and temperature, and offers several advantages such as repeatability of fabrication, robust structure, and compact size, which further benefits its practical sensing applications [105].

4.1 Background and literature review

Optical fiber sensors have attracted considerable attention due to the advantages such as compactness, light weight, high stability, repeatability, and immunity to electromagnetic interference. Strain measurement, one of the most important applications of optical fiber sensors, has been widely applied in many fields, especially in structural health monitoring for aircrafts, dams, towers, bridges, skyscrapers, railways, highways, and so on. In the past few years, fiber-based strain sensors have been demonstrated with various types of schemes, for example, an FBG in a waveguide-array microstructured optical fiber [102] or an all-solid photonic bandgap fiber [106], an LPFG in an index-guiding photonic crystal fiber (PCF) [107] or an MCF[108], in-line MZIs [71, 93, 106, 109] and all-fiber FPIs [79, 110-112]. Their sensitivities to strain were typically about $1 \text{ pm}/\mu\epsilon$ for FBGs, less than $10 \text{ pm}/\mu\epsilon$ for LPFGs or MZIs, and less than $16 \text{ pm}/\mu\epsilon$ for FPIs. In order to further enhance the strain sensitivity, some additional designs have been demonstrated based on FPIs. For

instance, an FPI based on a rectangular-shape air cavity with the wall thickness of about $1\mu\text{m}$ achieved a strain sensitivity as high as $43.0\text{ pm}/\mu\epsilon$ [113]. By combining Vernier effect, another FPI consisting of two cascaded air cavities was reported to achieve a strain sensitivity of $47.14\text{ pm}/\mu\epsilon$ [114]. However, because of the air-cavities of FPI structures, the devices have a low mechanical strength [110]. The previously reported sensing schemes encounter the problems of a relatively low sensitivity or weak mechanical strength. Therefore, strain sensors with a high sensitivity and a robust mechanical structure are in high demand.

In this chapter, we will demonstrate another approach to achieve an ultra-high strain sensitivity by introducing an HS into an MCF. HSs in optical fibers, also called chiral structures, refer to the fiber structures that are deformed into helical shapes rather than conventional fibers with straight cores. This special structure is usually fabricated by continuously twisting optical fibers when they pass through a miniature heat zone [115, 116]. Since V. I. Kopp *et al.* reported two types of chiral LPFGs by twisting an optical fiber with a noncircular core into HSs in 2004 [116], such particular fiber structure has attracted increasing interests due to its unique polarization dependence as well as very promising sensing applications [117, 118]. For example, V. I. Kopp's group demonstrated sensors for measurement of liquid level and temperature [117], pressure and temperature [119]. Besides, P. St. J. Russell's group demonstrated helical PCFs to convert the fundamental core mode to a series of cladding orbital angular momentum states at certain wavelengths, causing a few dips in the transmission spectrum [120]. Afterwards, they reported a sensor for simultaneous measurement of axial strain and twist by utilizing a helical PCF, the strain sensitivity was about $1.18\text{ pm}/\mu\epsilon$ [121].

In our work, an all-solid heterogeneous MCF was locally twisted into an HS and then spliced between two short sections of MMFs to construct an in-line MZI. The HS was fabricated in the MCF by a CO_2 laser splicing system (Fujikura, LZM-100). In the region of the HS, the outer cores were deformed into helical cores while the center core was kept straight. Due to the HS, a maximum strain sensitivity as high as $-61.8\text{ pm}/\mu\epsilon$ was achieved. It is about 56 times higher than that of the same MCF-based MZI [71]. Since the sensor is composed of all-solid fibers which have the same cladding diameter,

it has a relatively better mechanical strength compared with air-cavity-based schemes. Furthermore, the proposed sensor can also measure strain and temperature simultaneously. The cross-sensitivity to temperature can be eliminated.

4.2 Sensor design and fabrication

The MCF used in this work is the same with that shown in Fig. 3.5. Figure 4.1(a) illustrates the measured refractive index profile of the MCF, the inset of Fig. 4.1(a) is the microscope image of the cross-section of the MCF. The six outer cores are designed with G.657.B3 refractive index profile, and they have deep trenches. The center core is designed with G.652 refractive index profile and a shallow trench. Compared with the pure silica cladding, the refractive index differences of the outer cores, center core, trenches of the outer cores and trench of the center core are about 5.3×10^{-3} , 4.7×10^{-3} , -3.8×10^{-3} and -6×10^{-4} , respectively. More geometrical information about the MCF can be found in Fig. 3.5. Figure 4.1(b) illustrates the schematic diagram of the proposed in-line MZI-based sensor structure, in which a segment of MCF with a HS is spliced between two segments of MMFs, and then connected to a light source and an OSA with SMFs. One of the MMFs is utilized to couple the light into all the seven cores and the cladding of the MCF, while the other MMF is used to recombine the light into the lead-out SMF. It should be noted that all the fusion splicing is implemented without a lateral offset. The cladding diameter and core diameter of the MMFs are 125 μm and 105 μm , respectively. The lengths of the two MMFs should be chosen to be as short as possible so that the phase differences of their guided modes could be neglected [122].

Figure 4.1. (a) The measured refractive index profile of the MCF. The inset is the cross-sectional microscope image of the MCF. (b) Configuration of the proposed in-line MZI based sensor.

To investigate the influence of the MMF length, a segment of MMF with three different lengths was spliced between two SMFs, and the transmission spectra were recorded, respectively. For easy fabrication, the lengths of the MMF were selected to be 1 mm, 2 mm and 3 mm. The spectra of the SMF-MMF-SMF structures are illustrated in Fig. 4.2. As can be seen, when the length was 1 mm, almost no interference was generated, hence the phase difference of its guided modes can be neglected. The interference appeared when the length was 2mm, and more obvious interference was formed for the length of 3 mm. Thus, for the proposed sensor, as the MMF length was 1 mm, the MMF almost did not generate interference spectrum by itself.

Even though the MMF length can affect the coupling efficiency, larger or smaller insertion loss caused by MMFs will not apparently affect the proposed sensor performance. To further investigate the influence of the MMF length on the coupling efficiency, beam propagation method (BPM) was utilized to simulate the light propagation in an SMF-MMF-MCF structure. Since the interference appeared when the MMF length was 2 mm, to avoid the MMF generating interference by it itself, the MMF length should be less than 2 mm. For the simulation, the length of the SMF, MMF and MCF were 500 μm , 2000 μm and 2500 μm , respectively. The refractive

indices were set to be 1.4607/1.444, 1.449/1.444 for the core/cladding of the MMF and SMF, respectively. The core diameter and length of the SMF were set to be $8.2\text{ }\mu\text{m}$ and $500\text{ }\mu\text{m}$. Figure 4.3(a) shows the simulated electric field distribution along the SMF-MMF-MCF structure at the wavelength of 1550 nm . Figure 4.3(b) shows the simulated normalized propagating powers along the SMF-MMF-MCF structure for pathway 1 and pathway 2. Pathway 1 was from the SMF core to the MMF core, and then to one of the outer cores of the MCF. Pathway 2 was from the SMF core to the MMF core, and then to the center core of the MCF. As shown in Fig. 4.3(b), the normalized propagating powers decreased dramatically along the first $500\text{ }\mu\text{m}$ section of the MMF. During the section from $500\text{ }\mu\text{m}$ to $2000\text{ }\mu\text{m}$ of the MMF, the powers changed slightly. Thus, for easy fabrication of the sensor, the lengths of the MMFs were chosen to be 1 mm .

Figure 4.2. Transmission spectra of the SMF-MMF-SMF structures

Figure 4.3. (a) Simulated distribution of the propagating field and (b) normalized propagating power along the SMF-MMF-MCF (without a HS) structure.

To demonstrate that the light can be coupled into all the seven cores of the MCF within the proposed sensor, BPM was utilized to simulate the light propagation in an SMF-MMF-MCF structure by setting the length of the MMF as 1 mm. It's worth noting that, to simplify the simulation, the MCF section was set to be without an HS. In the simulation, the length of the MCF was set to be 3500 μm . Figure 4.4 shows the simulated electric field distribution along the SMF-MMF-MCF structure at the wavelength of 1550 nm when the MMF length was 1 mm. As can be seen, the incident light from the SMF expanded obviously in the MMF section and then was coupled into the center core, outer cores and cladding of the MCF. The outer cores have stronger field distribution than the center core. And the field distribution in the outer cores has minimum value on the axis. This phenomenon should be mainly caused by the cladding modes coupling with the core mode. Furthermore, the near-field light distribution at the end facet of the MCF without an HS was measured by utilizing the beam view

system mentioned in chapter 3. As shown in Fig. 4.5, all the seven cores were coupled with light obviously and a proportion of light was distributed in the cladding as well. The light in the center core was stronger than that in the outer cores. The measured result is accordance with the simulation result.

Figure 4.4. Simulated distribution of the propagating field along the SMF-MMF-MCF(without an HS) structure when the length of the MMF is 1 mm.

Figure 4.5. Measured light distribution at the end facet of the MCF without an HS.

The HS was fabricated by using the CO₂ laser splicing system with the manual controlling mode. The total twisted angle of the HS for the proposed sensor sample used in this work was 6π rad. Figure 4.6 illustrates the process of the HS fabrication in the MCF. It involves three main steps. In step 1, as shown in Fig. 4.6(a), a segment of the MCF with the coating layer stripped was fixed straightly between the two stages of LZM-100. The distance between the two stages was about 45mm. In step 2, as shown in Fig. 4.6(b), the rotation motor of one stage was rotated by 1π . Then the 1π pre-torsion was distributed along the whole MCF between the two stages. In step 3, as shown in Fig. 4.6(c), after using the CO₂ laser to heat the MCF, the pre-torsion of 1π was concentrated into a small region. Since the tuning range of the torsion for the two rotation motors is from -1π to 1π , in order to apply larger pre-torsion into the MCF, the rotation motor of the other stage was rotated by -1π , then the MCF was heated by the laser. Thus a pre-torsion of 2π was introduced into the small region of the MCF. Then the angles of two rotation motors were set to be 0° , and the two theta motors rotated automatically to their original position along the same direction. The aforementioned steps were repeated until a total pre-torsion of 6π was applied into the MCF. Figure 4.6(d) illustrates the microscope image of the side view of the HS with a total pre-torsion of 6π . The length of the twisted region is approximately $750\mu\text{m}$. Owing to the programmable controller and the stability of LZM-100, the HS fabrication is repeatable and simple. Furthermore, the twisted angle can also be controlled flexibly.

Figure 4.6. Schematic diagrams of the process of the helical structure fabrication. (a) Before adding pre-torsion. (b) The pre-torsion is distributed along the MCF without

laser heating. (c) The pre-torsion is concentrated into a small region after heating by the CO₂ laser. (d) Side view microscope image of the MCF with an HS.

4.3 Principle of operation

For our proposed sensor, the length of the twisted part is about 750 μm (only very few periods), which are too few to generate apparent LPFG effect compared with the chiral LPFG reported by V. I. Kopp [118]. On the other hand, the refractive index differences among the center core, outer cores, and cladding, and the length difference between the center core and the outer cores induced by the HS, will result in phase differences among the modes propagating along the MCF. Thus, a series of Mach-Zehnder interferences can occur among the outer cores mode, center core mode, and cladding modes. Hence, we will focus on the operation principle of our proposed sensor configuration by analyzing the interferences in it. For an interference pattern generated by N different compositions, the intensity can be expressed as [123]:

$$I = \sum_{i=1}^N I_i + 2 \sum_{i=1}^N \sum_{j=i+1}^N \sqrt{I_i I_j} \cos(\Delta\phi_{ij}), \quad (4.1)$$

where I_i and I_j represent the intensities of i -th mode and j -th mode. ϕ_{ij} denotes the accumulated phase difference between i -th mode and j -th mode. Despite the fact that more than one cladding modes may be excited and propagate through the MCF, it can be assumed that only one cladding mode dominates the interference with the core modes [62, 124]. In addition, since all the six outer cores have the same specifications, the light in the six outer cores is regarded as a whole to be involved in the interferences.

When the light passes through the sensor, the accumulated phase differences between the center core mode and cladding mode, the center core mode and outer core mode, the outer core mode and cladding mode, can be expressed by the following three formulas, respectively:

$$\phi_1 = \frac{2\pi[(n_{eff}^{ce} - n_{eff}^{cl})(L - L_H) + (n_{eff}^{ceH} - n_{eff}^{clH})L_H]}{\lambda}, \quad (4.2)$$

$$\phi_2 = \frac{2\pi[(n_{eff}^{ou} - n_{eff}^{ce})(L - L_H) + (n_{eff}^{ouH} L_{ouH} - n_{eff}^{ceH} L_H)]}{\lambda}, \quad (4.3)$$

$$\phi_3 = \frac{2\pi[(n_{eff}^{ou} - n_{eff}^{cl})(L - L_H) + (n_{eff}^{ouH} L_{ouH} - n_{eff}^{clH} L_H)]}{\lambda}, \quad (4.4)$$

where n_{eff}^{ce} (n_{eff}^{ceH}), n_{eff}^{cl} (n_{eff}^{clH}) and n_{eff}^{ou} (n_{eff}^{ouH}) represent the refractive indices of the center core mode, the cladding mode and the outer core mode in the non-helical part (helical part), respectively. L , L_H and L_{ouH} represent the lengths of the total MCF, the center core and outer cores in the helical part, respectively. λ is the operating wavelength. The physical length of the outer cores in the helical part can be calculated by

$$L_{ouH} = \frac{\psi \sqrt{(2\pi d)^2 + [2\pi L_H / \psi]^2}}{2\pi}, \quad (4.5)$$

where d is the distance between the outer core and the center core, ψ represents the total torsion angle of the helical structure.

When the phase difference $\phi = (2m+1)\pi$, ($m=0, 1, 2, 3\dots$), the destructive interference condition is satisfied. By substituting this condition into Eq. (4.2), Eq. (4.3) and Eq. (4.4), the respective resonant wavelength dips can be written as:

$$\lambda_1 = \frac{2[(n_{eff}^{ce} - n_{eff}^{cl})(L - L_H) + (n_{eff}^{ceH} - n_{eff}^{clH})L_H]}{2m+1}, \quad (4.6)$$

$$\lambda_2 = \frac{2[(n_{eff}^{ou} - n_{eff}^{ce})(L - L_H) + (n_{eff}^{ouH} L_{ouH} - n_{eff}^{ceH} L_H)]}{2m+1}, \quad (4.7)$$

$$\lambda_3 = \frac{2[(n_{eff}^{ou} - n_{eff}^{cl})(L - L_H) + (n_{eff}^{ouH} L_{ouH} - n_{eff}^{clH} L_H)]}{2m+1}. \quad (4.8)$$

When external axial strain ε is applied to the sensor, the dimension of the sensor and the refractive indices of the propagating modes will be changed. ε is defined as the relative length physical change of the fiber, i.e. $\varepsilon = \Delta L / L = \Delta L_H / L_H$, where ΔL and ΔL_H represent the strain-induced length changes of the whole MCF and the center core in

helical part, respectively. The radial strain $\varepsilon_r = -\nu\varepsilon$, ν is the Poisson's ratio with a typical value of 0.16 for optical fibers [44]. Hence, the distance between the outer core and the center core under the external axial strain ε can be expressed as $d_\varepsilon = (1 - \nu\varepsilon)d$.

According to Eq. (4.6), the axial strain induced wavelength shift for λ_1 can be approximately expressed as [125, 126]:

$$\begin{aligned} \Delta\lambda_{1,\varepsilon} = & \frac{2}{2m+1} \left[\frac{\partial(n_{eff,\varepsilon}^{ce} - n_{eff,\varepsilon}^{cl})}{\partial\varepsilon} (L_\varepsilon - L_{H,\varepsilon}) + (n_{eff,\varepsilon}^{ce} - n_{eff,\varepsilon}^{cl}) \frac{\partial(L_\varepsilon - L_{H,\varepsilon})}{\partial\varepsilon} \right] \varepsilon \\ & + \frac{2}{2m+1} \left[\frac{\partial(n_{eff,\varepsilon}^{ceH} - n_{eff,\varepsilon}^{clH})}{\partial\varepsilon} L_{H,\varepsilon} + (n_{eff,\varepsilon}^{ceH} - n_{eff,\varepsilon}^{clH}) \frac{\partial L_{H,\varepsilon}}{\partial\varepsilon} \right] \varepsilon, \end{aligned} \quad (4.9)$$

It is worth noting that the subscript “ ε ” means the variables are under axial strain. Since $\partial(L_\varepsilon - L_{H,\varepsilon})/\partial\varepsilon$ and $\partial L_{H,\varepsilon}/\partial\varepsilon$ can be approximated as $(L - L_H)$ and L_H , respectively, $n_{eff,\varepsilon}^{ce} \approx n_{eff,\varepsilon}^{ceH}$, $n_{eff,\varepsilon}^{cl} \approx n_{eff,\varepsilon}^{clH}$, and L_ε is much larger than $L_{H,\varepsilon}$. Thus Eq. (4.9) can be simplified as:

$$\begin{aligned} \Delta\lambda_{1,\varepsilon} & \approx \frac{2}{2m+1} \left[\frac{\partial(n_{eff,\varepsilon}^{ce} - n_{eff,\varepsilon}^{cl})}{\partial\varepsilon} (1 + \varepsilon)L + (n_{eff,\varepsilon}^{ce} - n_{eff,\varepsilon}^{cl})L \right] \varepsilon \\ & \approx \frac{2}{2m+1} \left[\frac{\partial(n_{eff,\varepsilon}^{ce} - n_{eff,\varepsilon}^{cl})}{\partial\varepsilon} L + (n_{eff,\varepsilon}^{ce} - n_{eff,\varepsilon}^{cl})L \right] \varepsilon. \end{aligned} \quad (4.10)$$

When axial strain is applied to the fiber, the radii and refractive indices of the fiber core and fiber cladding decrease, which results in a reduction in the normalized frequency V . More power can be coupled into the cladding from the core, therefore, the difference of the effective refractive indices between the core and cladding decreases [126]. The influence of the sensor length increase has a smaller impact than the reduction of the effective refractive indices difference on the resonant wavelength, thus the resonant wavelength will shift to shorter wavelength side when the axial strain increases i.e., $\Delta\lambda_{1,\varepsilon} < 0$ [20]. Typically, for the conventional MZIs, the resonant wavelengths show linear strain sensitivities [127, 128].

Similarly, the strain-induced wavelength shifts for λ_2 and λ_3 can be approximately described by:

$$\begin{aligned}\Delta\lambda_{2,\varepsilon} \approx & \frac{2}{2m+1} \left(\frac{\partial n_{eff,\varepsilon}^{ou}}{\partial \varepsilon} - \frac{\partial n_{eff,\varepsilon}^{ce}}{\partial \varepsilon} + n_{eff,\varepsilon}^{ou} - n_{eff,\varepsilon}^{ce} \right) L\varepsilon \\ & + \frac{2}{2m+1} \left[\frac{\partial n_{eff,\varepsilon}^{ou}}{\partial \varepsilon} (L_{ouH,\varepsilon} - L_{H,\varepsilon}) + n_{eff,\varepsilon}^{ou} \left(\frac{\partial L_{ouH,\varepsilon}}{\partial \varepsilon} - L_{H,\varepsilon} \right) \right] \varepsilon\end{aligned}\quad (4.11)$$

$$\begin{aligned}\Delta\lambda_{3,\varepsilon} \approx & \frac{2}{2m+1} \left(\frac{\partial n_{eff,\varepsilon}^{ou}}{\partial \varepsilon} - \frac{\partial n_{eff,\varepsilon}^{cl}}{\partial \varepsilon} + n_{eff,\varepsilon}^{ou} - n_{eff,\varepsilon}^{cl} \right) L\varepsilon \\ & + \frac{2}{2m+1} \left[\frac{\partial n_{eff,\varepsilon}^{ou}}{\partial \varepsilon} (L_{ouH,\varepsilon} - L_{H,\varepsilon}) + n_{eff,\varepsilon}^{ou} \left(\frac{\partial L_{ouH,\varepsilon}}{\partial \varepsilon} - L_{H,\varepsilon} \right) \right] \varepsilon\end{aligned}\quad (4.12)$$

where $L_{ouH,\varepsilon} = \left[(\psi d_\varepsilon)^2 + L_{H,\varepsilon}^2 \right]^{0.5}$. For both Eq. (4.11) and Eq. (4.12), the first terms change linearly while the second terms change nonlinearly with axial strain variation. Therefore, both λ_2 and λ_3 will shift nonlinearly to axial strain variation.

To demonstrate the HS can improve the strain sensitivity, we analyze Eq. (4.11) for the two cases, i.e. $\psi=0$ and $\psi>0$. If $\psi=0$, which means no HS is involved in the MCF, then $L_{ouH,\varepsilon} = L_{H,\varepsilon}$, and $\partial L_{ouH,\varepsilon} / \partial \varepsilon_z = L_H$. Thus, according to Eq. (4.10), Eq. (4.11) can be simplified as:

$$\Delta\lambda_{2,\varepsilon,\psi=0} \approx \frac{2}{2m+1} \left(\frac{\partial n_{eff,\varepsilon}^{ou}}{\partial \varepsilon} - \frac{\partial n_{eff,\varepsilon}^{ce}}{\partial \varepsilon} + n_{eff,\varepsilon}^{ou} - n_{eff,\varepsilon}^{ce} \right) L\varepsilon. \quad (4.13)$$

If $\psi>0$, $L_{ouH,\varepsilon} > L_H$ and $\partial L_{ouH,\varepsilon} / \partial \varepsilon < L_H$. In addition, $\partial n_{eff}^{ou} / \partial \varepsilon < 0$ and $n_{eff}^{ou} > 0$, thus

$$\frac{\partial n_{eff,\varepsilon}^{ou}}{\partial \varepsilon} (L_{ouH,\varepsilon} - L_H) + n_{eff,\varepsilon}^{ou} \left(\frac{\partial L_{ouH,\varepsilon}}{\partial \varepsilon} - L_H \right) < 0. \quad (4.14)$$

Since $\Delta\lambda_{2,\varepsilon,\varphi=0} < 0$, when $\psi > 0$, according to Eq. (4.11) and inequality (4.14), $|\Delta\lambda_{2,\varepsilon,\psi=0}| < |\Delta\lambda_{2,\varepsilon,\psi>0}|$, which shows that the corresponding wavelength dip can have a larger wavelength shift when fabricating an HS in the MCF. In other words, the HS in the MCF can improve the strain sensitivity.

To investigate the influence of L_H on the strain sensitivity, the variations of $(L_{ouH,\varepsilon} - L_H)$ and $(\partial L_{ouH,\varepsilon} / \partial \varepsilon - L_H)$ with increasing L_H for a certain strain (e.g. $\varepsilon = 200 \mu\varepsilon$), were calculated, the results are shown in Fig. 4.7. For a certain total torsion angle, e.g. $\psi = 6\pi$ rad, $(L_{ouH,\varepsilon} - L_H)$ decreases and $(\partial L_{ouH,\varepsilon} / \partial \varepsilon - L_H)$ increases nonlinearly with increasing L_H , as shown in Fig. 4.7. These variation trends result in $|\Delta\lambda_{2,\varepsilon}|$ decreasing. In other words, for a certain ψ , the strain sensitivity becomes smaller with increasing L_H . When the applied strain increases, L_H is stretched to be longer, thus the strain sensitivity decreases. This reveals that the wavelength dips generated by the outer core mode interfering with the cladding mode or the center core mode have nonlinear strain responses.

Figure 4.7. Variations of $(L_{ouH,\varepsilon} - L_H)$ and $(\partial L_{ouH,\varepsilon} / \partial \varepsilon - L_H)$ with increasing L_H when $\psi = 6\pi$ rad.

When the temperature is changed, both the refractive index and dimension of the sensing fiber will be changed. Since the thermal-optic coefficient ($8.6 \times 10^{-6}/^{\circ}\text{C}$) is much larger than the thermal expansion coefficient ($5.5 \times 10^{-7}/^{\circ}\text{C}$) for silica [129], the dimension change induced by temperature variation can be neglected. Therefore, the wavelength shifts of the three resonant dips due to the temperature variation ΔT can be described by the following formulas, respectively:

$$\begin{aligned}\Delta\lambda_{1,T} &\approx \frac{2}{2m+1} \left[\frac{\partial(n_{\text{eff}}^{\text{ce}} - n_{\text{eff}}^{\text{cl}})}{\partial T} (L - L_H) + \frac{\partial(n_{\text{eff}}^{\text{ceH}} - n_{\text{eff}}^{\text{clH}})}{\partial T} L_H \right] \Delta T \\ &\approx \frac{2}{2m+1} \frac{\partial(n_{\text{eff}}^{\text{ce}} - n_{\text{eff}}^{\text{cl}})}{\partial T} L \Delta T,\end{aligned}\quad (4.15)$$

$$\begin{aligned}\Delta\lambda_{2,T} &\approx \frac{2}{2m+1} \left[\frac{\partial(n_{\text{eff}}^{\text{ou}} - n_{\text{eff}}^{\text{ce}})}{\partial T} (L - L_H) + \frac{\partial n_{\text{eff}}^{\text{ouH}}}{\partial T} L_{\text{ouH}} - \frac{\partial n_{\text{eff}}^{\text{ceH}}}{\partial T} L_H \right] \Delta T \\ &\approx \frac{2}{2m+1} \frac{\partial(n_{\text{eff}}^{\text{ou}} - n_{\text{eff}}^{\text{ce}})}{\partial T} L \Delta T,\end{aligned}\quad (4.16)$$

$$\begin{aligned}\Delta\lambda_{3,T} &\approx \frac{2}{2m+1} \left[\frac{\partial(n_{\text{eff}}^{\text{ou}} - n_{\text{eff}}^{\text{cl}})}{\partial T} (L - L_H) + \frac{\partial n_{\text{eff}}^{\text{ouH}}}{\partial T} L_{\text{ouH}} - \frac{\partial n_{\text{eff}}^{\text{clH}}}{\partial T} L_H \right] \Delta T \\ &\approx \frac{2}{2m+1} \frac{\partial(n_{\text{eff}}^{\text{ou}} - n_{\text{eff}}^{\text{cl}})}{\partial T} L \Delta T,\end{aligned}\quad (4.17)$$

where T represents the temperature. According to Eq. (4.15), Eq. (4.16) and Eq. (4.17), all the dips will shift linearly to longer wavelengths with temperature increasing. The thermal-optic coefficient of the pure silica cladding is smaller than that of the germanium-doped silica cores [130]. In addition, the thermal-optic coefficients of the center core and outer cores are similar, although there is a slight difference in the doping concentrations between the center core and outer cores. Therefore, the difference of the thermal-optic coefficients between the center core and outer cores is smaller than that between the cladding and cores. In other words, $\partial(n_{\text{eff}}^{\text{ou}} - n_{\text{eff}}^{\text{ce}})/\partial T$ is smaller than $\partial(n_{\text{eff}}^{\text{ce}} - n_{\text{eff}}^{\text{cl}})/\partial T$ and $\partial(n_{\text{eff}}^{\text{ou}} - n_{\text{eff}}^{\text{cl}})/\partial T$, which results in that the resonant

dip generated from the interference between the center core mode and outer core mode has a smaller temperature sensitivity than the other two types of resonant dips.

4.4 Results and discussions

To measure the transmission spectra of different cores of the MCF with the fabricated HS, the MCF with a total length of about 20 mm was spliced between a pair of fan-in/out 1x7 multiplexers. The total insertion loss of the two fan-in/out multiplexers is about 5 dB. The green curve and dark yellow curve in Fig. 4.8(a) represent the measured transmission spectra of the center core and one outer core, respectively. As shown, no obvious dips were observed in the spectra for both the center core and outer core. The spectrum of the outer core had a larger loss, which was mainly caused by the larger structure deformation and relatively larger mode-field mismatch with the multiplexers. The transmission spectra were measured again when the MCF with the HS was spliced between two segments of MMFs and then spliced between two SMFs. The lengths of the MMFs were about 1 mm. The total insertion loss of the devices was about 17 dB. The blue curve and red curve in Fig. 4.8(a) represent the transmission spectra when the lengths of MCF were about 21.5 mm and 7.8 mm, respectively. As shown, obvious inhomogeneous interferences spectra were obtained. This result suggests that the interference patterns were a superposition of multiple interferences with different free spectrum ranges (FSRs). It is further validated by the corresponding spatial frequency spectra obtained by taking fast Fourier Transform (FFT), as shown in Fig. 4.8(b).

For a normal MZI, e.g., if the MCF is not twisted, the relationship between the differential modal group index and spatial frequency can be described by [131]:

$$\Delta m_{eff} = \xi \lambda_0^2 / L_{MZI}, \quad (4.18)$$

where Δm_{eff} , ξ , λ_0 and L_{MZI} represent the differential modal group index, the spatial frequency, the center wavelength and the interferometer length, respectively. For our proposed sensor structure, since the length of the twisted region was much smaller than the total length of the MCF, we can still use Eq. (4.18) to roughly analyze the spatial

frequency. When the length of MCF was 21.5 mm, there were three strong peaks and a few weaker peaks in the spatial frequency spectrum. The three strongest peaks located at 0.01 nm^{-1} , 0.0253 nm^{-1} , and 0.0379 nm^{-1} . The Δm_{eff} corresponding to peak 0.01 nm^{-1} was approximately calculated to be 9.8×10^{-4} , which is close to the material refractive index difference between the center core and the outer cores. For 0.0253 nm^{-1} and 0.0379 nm^{-1} , the corresponding Δm_{eff} were calculated to be 2.8×10^{-3} and 3.7×10^{-3} . Moreover, the order of magnitude of the material refractive index difference between the center core and cladding, as well as that between the outer cores and cladding is minus three. Hence the inhomogeneous interference pattern should be mainly caused by the superposition of the interferences between the center core mode and outer core mode, center core mode and cladding mode, outer core mode and cladding mode. The weaker peaks in the spatial frequency spectrum could be attributed to non-uniformity of the outer cores and the excited high-order cladding modes. When the length of the MCF was 7.8 mm, the spatial frequency spectrum only had two dominant peaks locating at 0.0075 nm^{-1} and 0.015 nm^{-1} . Their corresponding Δm_{eff} were calculated to be 2.0×10^{-3} and 4.0×10^{-3} . It implies that the total interference pattern contained at least the interference between the center core mode and cladding mode and that between the outer core mode and cladding mode. The spatial frequency component of the interference between the center core mode and outer core mode was missing in the FFT spectrum due to the limit range of the measured optical spectrum shown in Fig. 4.8(a) and its much larger FSR. The FSR of the interference between the center core mode and outer core mode was around 450 nm, which could be estimated by $FSR \approx \lambda_0^2 / (\Delta m_{eff} L)$. Nevertheless, it is still possible that one of the resonant dips shown in Fig. 4.8(a) with red curve was generated from the interference between the center core mode and outer core mode. The resonant dips originated from different interferences are expected to respond differently to strain, temperature, or other parameters.

Figure 4.8. (a) Transmission spectra of the MCF with the HSs for different configurations. The green curve and dark yellow curve represent the measured transmission spectra of the center core and one outer core, respectively, when the MCF was spliced between a pair of fan in/out devices. The red curve and blue curve are the measured transmission spectra of the MZI structures when the length of MCF was 21.5 mm and 7.8 mm, respectively. (b) Spatial frequency spectra of the corresponding transmission spectra.

As shown in Fig. 4.1(b), the configuration with the total MCF length of 7.8 mm was utilized as our proposed sensing head. In order to investigate its strain response, the proposed sensor was clamped straightly between two stages with a distance of about 250 mm. One of the stages was fixed, while the other one was moved axially to the opposite direction to stretch the sensor. As the cross-sectional area and Young's Modulus of the MCF are almost the same with those of the MMFs and SMFs, the axial strain ε applied on the sensor can be calculated by the relative length change of the fiber. When the axial strain was increased from 0 to 880 $\mu\varepsilon$, Dip A, Dip B, and Dip C shifted to shorter wavelengths, as illustrated in Fig. 4.9(a). The interference dip wavelength of Dip A responded to axial strain linearly and the corresponding sensitivity was measured to be -0.011 nm/ $\mu\varepsilon$ with the coefficient of determination (R-square) of about 0.995, as shown in Fig. 4.9(b). Different from Dip A, both Dip B and Dip C shifted to shorter wavelengths nonlinearly with different strain sensitivities. By piecewise linearly fitting the measured wavelengths, the linear strain sensitivities of Dip B and Dip C were -0.0618 nm/ $\mu\varepsilon$ and -0.0393 nm/ $\mu\varepsilon$ in the strain range from 0 to 200 $\mu\varepsilon$, -0.0327 nm/ $\mu\varepsilon$ and -0.0244 nm/ $\mu\varepsilon$ in the strain range from 200 to 480 $\mu\varepsilon$, -0.0146 nm/ $\mu\varepsilon$ and -0.0104 nm/ $\mu\varepsilon$ in the strain range from 480 to 880 $\mu\varepsilon$, respectively, as shown in Fig. 4.9(c). The strain responses of Dip B and Dip C were nonlinear for whole strain range from 0 to 880 $\mu\varepsilon$, and their strain sensitivities were much smaller in larger strain range. According to the aforementioned theoretical analysis on the strain responses, Dip A should be generated from the interference between the center core mode and cladding mode because of its linear response to the axial strain, while Dip B and Dip C should be dominated by the outer core mode interfering with the cladding mode or the center core mode.

Figure 4.9. (a) Spectral shift of Dip A, Dip B and Dip C with varying axial strain. (b) Wavelength response of Dip A to axial strain. (c) Wavelength responses of Dip B and Dip C to axial strain.

Temperature responses of the three dips were characterized by putting the fiber with the sensor head in the groove of a column oven with temperature precision of 0.1°C. To be kept straight, the fiber was stretched with a tiny tension. As shown in Fig. 4.10(a), all the three dips shifted to longer wavelengths when the sensor was heated from 25 °C to 95 °C with a step of 10 °C. The corresponding temperature sensitivities of Dip A, Dip B, and Dip C, as shown in Fig. 4.10(b), were measured to be 0.056 nm/°C, 0.026 nm/°C, and 0.044 nm/°C, respectively. Comparing with Dip A and Dip C, Dip B has a much smaller temperature sensitivity. Since the difference of the thermal-optic coefficients between the center core and outer cores is smaller than that between the cladding and cores, the resonant dip generated from the interference between the center core mode and outer core mode has a smaller temperature sensitivity than the resonant dips generated from the interference between the cladding mode and center core mode as well as that between the cladding mode and outer core mode. Therefore, Dip B should be generated from the interference between the outer core mode and the center core mode. Combining all the aforementioned discussion, we can infer that Dip C should be dominated by the interference between the outer core mode and cladding mode. The experimental results of the characterizations of axial strain and temperature responses match the theoretical prediction very well.

Moreover, since the three dips response differently to axial strain and temperature, by selecting two dips as the sensing indicators, e.g., Dip A and Dip B, the proposed sensor can be utilized to measure axial strain and temperature simultaneously by constructing matrixes [102]:

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} -0.011 & 0.056 \\ -0.0618 & 0.026 \end{bmatrix}^{-1} \begin{bmatrix} \delta\lambda_1 \\ \delta\lambda_2 \end{bmatrix}, 0 \mu\varepsilon \leq \varepsilon \leq 200 \mu\varepsilon \quad (4.19)$$

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} -0.011 & 0.056 \\ -0.0327 & 0.026 \end{bmatrix}^{-1} \begin{bmatrix} \delta\lambda_1 \\ \delta\lambda_2 \end{bmatrix}, 200 \mu\varepsilon \leq \varepsilon \leq 480 \mu\varepsilon \quad (4.20)$$

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} -0.011 & 0.056 \\ -0.0146 & 0.026 \end{bmatrix}^{-1} \begin{bmatrix} \delta\lambda_1 \\ \delta\lambda_2 \end{bmatrix}, 480 \mu\varepsilon \leq \varepsilon \leq 880 \mu\varepsilon \quad (4.21)$$

Figure 4.10. (a) Transmission spectra of the proposed sensor with varying temperature. The insets show the spectral shifts of Dip B and Dip C. (b) Wavelength responses of Dip A, Dip B and Dip C to temperature variation.

4.5 Summary

In this chapter, we have proposed and experimentally demonstrated a highly sensitive strain sensor with a compact size based on a helical structure fabricated in an all-solid heterogeneous multicore fiber. The fabrication of the helical structure was introduced in detail. The length of the sensor head is about 1 cm. The proposed sensor exhibits a high strain sensitivity of $-61.8 \text{ pm}/\mu\epsilon$ in the strain range from 0 to $200 \mu\epsilon$. To the best of our knowledge, this is the highest strain sensitivity comparing with the previously reported strain sensors based on all-fiber interferometers. Furthermore, this sensor can be applied to discriminate axial strain and temperature. Besides, this device has a relatively better mechanical strength because all the segments are all-solid fibers with the same physical diameter. With the advantages such as low cost, repeatability of fabrication, compact size, robust structure, high sensitivity, and strain-temperature discrimination, the proposed strain sensor shows great potential in the applications of structural health monitoring.

Chapter 5 Directional Torsion Sensor with Temperature Discrimination

At the beginning of this chapter, the optical fiber-based torsion sensors are briefly introduced. Then, a directional torsion sensor based on an MZI formed in an MCF with a ~ 570 μm -long HS is proposed and experimentally demonstrated. The HS was fabricated into the MCF by simply pre-twisting and then heating with a CO_2 laser splicing system. This device shows the capability of directional torsion measurement from -17.094 rad/m to 15.669 rad/m with the sensitivity of ~ 0.118 $\text{nm}/(\text{rad/m})$. Moreover, since the multiple interferences respond differently to torsion and temperature simultaneously, the temperature cross-sensitivity of the proposed sensor can be eliminated efficiently. Besides, the sensor owns other merits such as easy fabrication and good mechanical robustness [132].

5.1 Background and literature review

Torsion is one of the most important mechanical parameters for monitoring structures and recently torsion sensors are widely used in many practical applications, for instance, structural health monitoring [133], robot position tracking [134]. Thanks to the intrinsic advantages such as compact size, easy integration, immunity to electromagnetic interference and high sensitivity, optical fiber based torsion sensors have attracted extensive research interests and have been demonstrated with different schemes such as fiber gratings or fiber interferometers. Due to the circular symmetry of normal fibers, most of the fiber-based torsion sensors can only measure quantitatively the applied torsion but without the twist direction. In order to achieve the capability of twist direction discrimination, some approaches have been demonstrated to break fibers' circular symmetry. The first approach is using an asymmetric fiber as the sensing unit such as polarization-maintaining fiber (PMF) or photonic crystal fiber based Sagnac interferometers [135, 136]. The second approach is using various kinds of micro-

machining means to achieve the fibers' asymmetry such as fabricating an LPFG in a single SMF with a CO₂ laser [137] or a phase-shifted FBG in an SMF with a femtosecond laser [138], and introducing two dissimilar abrupt tapers in a highly Er/Yb co-doped fiber [139] or a twisted taper in a PMF [140]. Another micro-machining method, fabricating HSs in fibers, has received considerable attention recently. For instance, a helical LPFG (HLPFG) [141] or paired HLPFGs [142] were inscribed in SMFs by CO₂ lasers. L. A. Fernandes *et al.* proposed an interesting scheme for torsion sensor by fabricating a helical waveguide (HW) in the cladding of an SMF by a femtosecond laser [143]. The aforementioned approaches exhibited good performance but still had some drawbacks. For instance, the fabrication of PCFs is costly and relatively complicated, which are the barriers to widespread applications of PCF-based torsion sensors. The conventional LPFG or HLPFGs usually encounter a problem of temperature cross-sensitivity [137, 141]. The fabrication of the phase shifted FBG or HW by a femtosecond laser requires ultrahigh precision and the process is complicated, because not only the laser beam needs to be precisely aligned and focused inside the fiber, but the fiber and the objective lens need to be immersed in index-matching oil [138, 143]. The taper regions result in a relatively worse mechanical strength [139, 140]. The paired HLPFGs is easily affected by non-uniform external temperature perturbation due to its long length of about 60 mm [142]. Thus, an easy method of fabricating a torsion sensor with twist direction discrimination and eliminating temperature cross-sensitivity is in high demand.

In chapter 4, we have proposed and demonstrated the fabrication of HSs in an MCF by utilizing a CO₂ laser splicing system. The fabrication process of the HS is easy and repeatable [105]. In this chapter, we experimentally demonstrate a torsion sensor based on an MZI formed in an all-solid MCF with an HS. The length of the HS is about 570 μm , which is much shorter than that of the whole MCF. The proposed sensor can measure torsion and determine the twist direction simultaneously, and the temperature cross-sensitivity can be eliminated. In addition, the proposed sensor offers easy fabrication and has good mechanical strength due to all the segments of the sensor having the same cladding diameter and all-solid structures.

5.2 Configuration and principle

The configuration of the HS-based sensor is depicted in Fig. 5.1, the inset shows the cross-sectional microscope image of the MCF used in this work, it is the same with that in chapter 3 and chapter 4. The . In the HS region, the outer cores and cladding were twisted into helical shapes while the center core was almost kept straight. As a result, the effective optical path lengths, and thus the effective refractive indices of the outer core mode and cladding mode were increased, while that of the center core mode was almost kept unchanged [144]. To construct the sensor, firstly, an ultra-short HS was permanently introduced into the MCF, the description of the HS fabrication method can be found in [105]. Then a segment of the MCF with the fabricated HS was connected between two MMFs via fusion splicing. The cladding and core diameters of the MMFs are 125 μm and 105 μm , respectively. Since different modes passing through the MMFs will accumulate phase differences, in order to reduce their influence on the interference spectrum of the sensor, the lengths of the MMFs should be chosen as short as possible [122]. In this work, the lengths of the MMFs were about 1 mm. At last, the sample was spliced with the lead-in and lead-out SMFs. One of the MMFs acts as a splitter coupling light from the lead-in SMF into all the seven cores and cladding, while the other one acts as a combiner coupling the light back to the lead-out SMF.

Figure 5.1. Configuration of the proposed sensor structure. The inset illustrates the cross-sectional micrograph of the MCF.

When the light propagates through the proposed structure, a series of interferences will occur among the center core mode, outer core mode, and cladding modes. The intensity of an interference generated by N different compositions can be expressed by

Eq. (4.1). When $\Delta\phi_{ij} = (2m+1)\pi$, where $m = 0, 1, 2, 3, \dots$, the destructive interference will result in the resonant dips locating at [105]:

$$\lambda_{ij} = \frac{2 \left[(n_{eff,i} - n_{eff,j}) L_s + (n_{eff,i}^H - n_{eff,j}^H) L_H \right]}{2m+1}, \quad (5.1)$$

where $n_{eff,i}$, $n_{eff,i}^H$, $n_{eff,j}$, $n_{eff,j}^H$ and L_s , L_H are the refractive indices of the i -th and j -th modes, and the physically propagating lengths in the straight region (pre-twisted region), respectively.

When external torsion is applied on the fiber, the photo-elastic effect will result in refractive index change, which can be described as [144, 145]

$$n(\tau) = n_0(1 + \rho^2 \tau^2)^{1/2} \approx n_0(1 + \rho^2 \tau^2 / 2), \quad (5.2)$$

where n_0 is the refractive index for the untwisted case, ρ is the radial distance to the center of the fiber, and τ is the twist rate. In the HS region, since a permanent torsion τ_0 has been pre-induced into the fiber and caused refractive index change, the corresponding refractive index with applied torsion can be written as

$$n^H(\tau) = n_0 \left[1 + \rho^2 (\tau \pm \tau_0)^2 / 2 \right] \quad (5.3)$$

where “+” and “−” means the applied torsion is in CW and CCW directions, respectively. As the radius of the center core is much smaller than ρ of the cladding and outer cores, the torsion induced refractive index change of the center core is almost zero, whereas that of the cladding and outer cores cannot be neglected [146].

According to Eq. (5.1), the applied torsion variation $\Delta\tau$ caused wavelength shift can be approximately expressed as:

$$\Delta\lambda_{ij,\tau} \approx \frac{2}{2m+1} \left[\frac{\delta(n_{eff,i} - n_{eff,j})}{\delta\tau} L_s + \frac{\delta(n_{eff,i}^H - n_{eff,j}^H)}{\delta\tau} L_H \right] \Delta\tau. \quad (5.4)$$

For the dips λ_1 generated from the interference between the center core mode and the cladding mode, the torsion variation caused wavelength shift can be expressed as:

$$\Delta\lambda_{1,\tau} \approx \frac{-2n_{eff,cl}\rho_{cl}^2 [\tau(L_s + L_H) \pm \tau_0 L_H] \Delta\tau}{2m+1}, \quad (5.5)$$

where $n_{eff,cl}$ and ρ_{cl} are the effective refractive index and the average radius of the cladding mode respectively. When τ_0 is much larger than τ , the right side of Eq. (5.5) is mainly determined by $\tau_0 L_H$, which implies the wavelength shift almost linearly to $\Delta\tau$ in a certain range. According to Eq. (5.5), the dips generated from the interference between the center core mode and the cladding mode will shift to shorter wavelength or longer wavelength when the applied torsion is increased in CW direction or in CCW direction, respectively.

Similarly, for the dips generated from the interferences between the center core mode and outer core mode, the outer core mode and cladding mode, the wavelength shifts can be expressed, respectively:

$$\Delta\lambda_{2,\tau} \approx \frac{2n_{eff,ou}\rho_{ou}^2 [\tau(L_s + L_H) \pm \tau_0 L_H] \Delta\tau}{2m+1}, \quad (5.6)$$

$$\Delta\lambda_{3,\tau} \approx \frac{2(n_{eff,ou}\rho_{ou}^2 - n_{eff,cl}\rho_{cl}^2) [\tau(L_s + L_H) \pm \tau_0 L_H] \Delta\tau}{2m+1}, \quad (5.7)$$

where $n_{eff,ou}$ is the effective refractive index, ρ_{ou} represents the average radius distance of the outer core mode. Comparing with $\Delta\lambda_1$, $\Delta\lambda_2$ and $\Delta\lambda_3$ change in an opposite trend with varying τ . In other words, the dips generated from the interferences between the outer core mode and other modes, will shift to longer wavelengths or shorter wavelengths when the applied torsion is increased in CW direction or CCW direction, respectively.

5.3 Results and discussion

Figure 5.2 (a) illustrates the side-view microscope photograph of the MCF with the fabricated HS. The total pre-twisted rotation angle of the HS was 4π . As shown, only screw-type deformation was introduced into the MCF while it was still kept straight as a whole. After the HS fabrication, the sensor was fabricated according to the configuration shown in Fig. 5.1. The lengths of the HS and the whole MCF were about $570\text{ }\mu\text{m}$ and 18.5 mm , respectively. The transmission spectrum of the sensor was measured by using a BLS (Infinon Research) and an OSA (Yokogawa AQ6370c). Several inhomogeneous interference notches can be observed in the spectrum as shown in Fig. 5.2(b). By using the FFT, the corresponding spatial frequency spectrum with three strong peaks was obtained, as shown in Fig. 5.2(c). The three strong peaks located at 0.0078 nm^{-1} , 0.0240 nm^{-1} and 0.0320 nm^{-1} , respectively.

Figure 5.2. (a) Side-view microscope photograph of the MCF with the fabricated HS. (b) Transmission spectrum of the proposed sensor. (c) Spatial frequency spectrum of the transmission spectrum.

Usually, to analyze the interference compositions, the differential modal group index Δm can be calculated according to the spatial frequency. The differential modal group index of a conventional MZI without pre-twisted interference arms can be approximately derived from the spatial frequency by Eq. (4.18) [131]. Since the length of the whole MCF is much larger than that of the HS, Eq. (4.18) can be still used to roughly analyze the interference compositions of the spectrum shown in Fig. 5.2(b). Here λ_0 and L are 1520 nm and 18.5 mm, thus the Δm corresponding to 0.0078 nm^{-1} , 0.0240 nm^{-1} and 0.0320 nm^{-1} were calculated to be 9.7×10^{-4} , 3.0×10^{-3} and 4.0×10^{-3} , respectively.

To further analyze the interference, the guided modes of the MCF and their corresponding effective refractive indices were simulated by using COMSOL Multiphysics 5.0 according to the MCF's physical parameters and refractive index profile. A perfect match layer (PML) was added to the outside of the cladding to absorb completely all the electric and magnetic field extending into the region [147]. The simulated mode-field distributions of the center core mode, outer core mode and the first order cladding mode at 1520 nm are shown in Figs. 5.3(a)-(c). Their effective refractive indices are 1.4461, 1.4466 and 1.4441, respectively. The effective refractive index differences between the center core mode and outer core mode, the center core mode and the first order cladding mode, the outer core mode and the first order cladding mode, are 5×10^{-4} , 2.0×10^{-3} , and 2.5×10^{-3} , respectively.

Comparing the simulated effective refractive index differences of the supported modes with the calculated differential modal group indices, the fact that the peak with the spatial frequency of 0.0078 nm^{-1} should be corresponding to the interference between the center core mode and outer core mode can be inferred. The other two peaks with the spatial frequencies of 0.0240 nm^{-1} and 0.0320 nm^{-1} could be attributed to the interferences between the center core mode and cladding mode, outer core mode and cladding mode respectively. The weak peaks observed in the spatial frequency spectrum could be mainly attributed to the higher order cladding modes.

(a)

(b)

(c)

Fig. 5.3. Simulated transverse mode field distribution of (a) center core mode, (b) outer core mode and (c) the first order cladding mode.

Figure 5.4. (a) Wavelengths responses of Dip A and Dip B to TR. (b) Transmission spectral evolutions of Dip A and Dip B with varying the twist rate.

In order to investigate the response to externally applied torsion, the sensor was stretched slightly and clamped between two fiber rotators (Thorlabs, PRM1/M) with a distance of about 245 mm. One rotator can be rotated in CW or CCW direction while the other one was fixed. The transmission spectra of the sensor were recorded with varying the rotation angle by a step of 20 degree corresponding to a twist rate step of

1.4245 rad/m. The twist rate was increased step by step to 22.792 rad/m in CW or CCW direction. The twist rate value was defined as positive in CW direction while negative in CCW direction. The wavelength responses of Dip A and Dip B to the twist rate variation are depicted in Fig. 5.4(a). As shown, when the twist rate was increased in CW direction, Dip A shifted linearly to shorter wavelengths for the twist rate up to 15.669 rad/m, and shifted back to longer wavelengths when the twist rate was larger than 15.669 rad/m. Different from Dip A, Dip B shifted to shorter wavelengths for the whole twist rate range up to 22.792 rad/m. When the twist rate was increased in CCW direction, both the two Dips shifted longer wavelengths firstly and then shifted back slightly. By linearly fitting the measured wavelengths, Dip A showed a torsion sensitivity of $-0.115 \text{ nm}/(\text{rad}/\text{m})$ with the coefficient of determination (R-square) of about 0.993 within the TR range from $-19.943 \text{ rad}/\text{m}$ to $15.669 \text{ rad}/\text{m}$, and Dip B exhibited a torsion sensitivity of $-0.118 \text{ nm}/(\text{rad}/\text{m})$ with R-square of about 0.992 within the twist rate range from $-17.094 \text{ rad}/\text{m}$ to $22.792 \text{ rad}/\text{m}$. As both the two dips showed blue shifts in CW direction and red shifts in CCW direction when the twist was increased, they should be generated from the interference between the center core mode and cladding mode. The two dips only showed linear responses to the twist rate variation for certain twist rate ranges, this phenomenon should be mainly caused by the twist-induced circular birefringence in the whole fiber between the two rotators [148]. To illustrate the transmission spectral evolutions of the dips clearly, the transmission spectra according to the twist rate range from $-17.094 \text{ rad}/\text{m}$ to $14.245 \text{ rad}/\text{m}$ with a step of $2.459 \text{ rad}/\text{m}$ are shown in Fig. 5.4(b).

The temperature responses of the dips were also investigated. To characterize the temperature responses, the sensor was fixed in a digital-controlled oven and kept straight under slight tension. The oven has a temperature precision of $0.1 \text{ }^{\circ}\text{C}$. The transmission spectra were measured by increasing the temperature from $30 \text{ }^{\circ}\text{C}$ to $90 \text{ }^{\circ}\text{C}$ with a step of $5 \text{ }^{\circ}\text{C}$. Both the dips exhibited red shifts with increasing the temperature, as shown in Fig. 5.5(a). Figure 5.5(b) shows the relationships between the collected wavelengths of the two dips and the temperature variation. The temperature sensitivities of Dip A and Dip B were measured to be $0.101 \text{ nm}/^{\circ}\text{C}$ and $0.054 \text{ nm}/^{\circ}\text{C}$ by linearly fitting, respectively.

Figure 5.5. (a) Transmission spectral evolutions of the two dips with temperature variation. (b) Relationships between the wavelength shift and temperature for the two dips.

The wavelength shifts of Dip A or Dip B caused by ambient temperature and applied torsion change can be expressed as:

$$\Delta\lambda_i = S_{\tau i}\Delta\tau + S_{Ti}\Delta T, (i = A, B), \quad (5.8)$$

where S_{τ_i} , S_{T_i} and ΔT represent the torsion sensitivity, temperature sensitivity, and temperature change, respectively. Since Dip A and Dip B response linearly and differently to temperature and torsion for the twist rate range from -17.094 rad/m to 15.669 rad/m, the torsion and temperature variations can be measured simultaneously by constructing the following matrix based on Eq. (5.8):

$$\begin{bmatrix} \Delta\tau \\ \Delta T \end{bmatrix} = \begin{bmatrix} S_{\tau A} & S_{TA} \\ S_{\tau B} & S_{TB} \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_A \\ \Delta\lambda_B \end{bmatrix}. \quad (5.9)$$

According to the experimental results, Eq. (5.9) can be rewritten as:

$$\begin{bmatrix} \Delta\tau \\ \Delta T \end{bmatrix} = \begin{bmatrix} -0.115 & 0.054 \\ -0.118 & 0.101 \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_A \\ \Delta\lambda_B \end{bmatrix}, -17.094 \leq \tau \leq 15.669. \quad (5.9)$$

5.4 Summary

In this chapter, we demonstrated a sensor for simultaneous measurement of directional torsion and temperature based on an in-line MZI formed in an MCF with a very short helical structure. By introducing the helical structure, the fiber circular asymmetry was achieved. The multiple interferences originated from the center core mode, outer core mode, and cladding mode was revealed by both FEM simulation and experimental spectrum analysis. The maximum torsion sensitivity of the proposed sensor reaches -0.118 nm/(rad/m) for the twist range from -17.094 rad/m to 15.669 rad/m. It is comparable with the sensitivity of the HLPG-based or HW-based torsion sensor [141, 143]. Although it is still lower than those of a twisted taper in a PMF [140] or paired HLPGs [142], the proposed sensor is valuable by overcoming their respective shortages such as a relatively worse mechanical strength for tapered fibers [140] and influence of non-uniform external temperature perturbation [142]. Compared with the previously reported schemes utilizing micro-machining means, the proposed sensor not only owns the capability of the discrimination of directional torsion and temperature but also takes the merits of easy fabrication and good mechanical robustness.

Chapter 6 Conclusions and Recommendations

6.1 Conclusions

MCFs based sensors have become a very attractive research topic, due to their intrinsic advantages, such as well-defined core separation, small size, light weight, repeatability, multiple channels, etc. MCFs have further advantages over bundles of fibers because all the cores of an MCF share the same cladding, which means that MCFs have an improved isothermal behaviour. The aims of this Ph.D. study are to explore and develop high-performance sensors based on MCFs by post-processing techniques such as grating fabrications or twisting MCFs. Three main works of my Ph.D. study have been presented in this thesis.

In chapter 1, the background, motivation, and objectives for my Ph.D. study have been introduced. In chapter 2, the types of MCF-based sensors and their recent development, as well as their working principles have been reviewed.

In chapter 3, my first work on inscribing FBGs in a heterogeneous MCF and its application for directional bending sensing has been presented. Due to the difference in refractive indices between the center core and outer cores, two FBGs with obviously different central wavelengths were measured by only splicing a segment of MMF between the MCF and the lead-in SMF. Since no complicated and expensive fan-out device was used, the proposed sensor offers several advantages, such as low cost and flexibility in fabrication. The maximum curvature sensitivity was about 0.128 nm/m^{-1} is much higher than the previously reported results based on eccentric FBGs [48, 50, 103, 104]. In addition, the sensor exhibited the capability of eliminating the temperature or strain cross-sensitivities.

In chapter 4, a highly sensitive strain sensor based on the MCF with an HS was proposed and demonstrated. The strain sensitivity is dozens of times higher than that of the sensors based on interferometers in MCFs [70, 71, 75, 149]. The process of

fabricating the HS in a non-twisted MCF was introduced in detail. Based on the HS, an in-line MZI sensor with an ultra-high strain sensitivity was proposed and demonstrated. The proposed sensor had the ability to discriminate axial strain and temperature, and offers several advantages such as repeatability of fabrication, robust structure, and compact size.

In chapter 5, a sensor for simultaneous measurement of directional torsion and temperature based on a segment of the MCF and an HS has been proposed and demonstrated. Compared with the previously reported torsion sensor schemes utilizing micro-machining means, the proposed sensor not only owns the capability of the discrimination of directional torsion and temperature but also takes the merits of easy fabrication and good mechanical robustness.

6.2 Recommendations for research

Firstly, with the development of heterogeneous MCFs with three or more different types of cores, the scheme of fabricating FBGs by the scanned phase mask method in such heterogeneous MCFs is promising for designing shape sensors without using fan-out devices. Comparing with the method of implementing a 3D shape sensor by fabricating Bragg grating waveguides one by one in a coreless optical fiber [150], our proposed method is much easier.

Secondly, spatially arrayed parallel channels of FPIs combined the Vernier effect can be fabricated based on MCFs, this scheme has the potential for directional bending with high sensitivities.

Thirdly, twisting MCFs with the CO₂ splicing system can result in structural deformation of the MCFs. Due to the helical shapes of the deformation, spatially arrayed parallel HLPFGs can be formed in the MCFs. After twisting, the structures of the formed HLPFGs in the outer cores are significantly different from that in the center core, they will have obviously different responses to stimuli, which make the HLPFGs suitable for multiparameter sensing with high sensitivities.

Torsion can generate axial strain which is mainly distributed in the cladding region [15], and axial strain increases the length of the fiber, in return, results in the twist rate decreasing. Thus, torsion and axial strain can affect each other, there is a cross-sensitivity between them. Designing a sensor based on MCF with HS for discriminating torsion, axial strain and temperature can be a research direction.

List of Publications

Journal papers

1. **H. Zhang** et al. Directional torsion and temperature discrimination based on multicore fiber with helical structure. *Opt. Express* **26**(1), 544-551(2018).
2. **H. Zhang** et al. Highly sensitive strain sensor based on helical structure combined with Mach-Zehnder interferometer in multicore fiber. *Sci. Rep.* **7**, 46633 (2017).
3. **H. Zhang** et al. Fiber Bragg gratings in heterogeneous multicore fiber for directional bending sensing. *J. of Opt.* **18**(8), 085705 (2016).
4. Z. Wu, P. P. Shum, X. Shao, **H. Zhang** et al. Temperature-and strain-insensitive curvature sensor based on ring-core modes in dual-concentric-core fiber. *Opt. Lett.* **41**(2),380-383(2016).
5. Z. Wu, **H. Zhang** et al. Supermode Bragg grating combined Mach-Zehnder interferometer for temperature-strain discrimination. *Opt. Express* **23**(26), 33001-330072(2015).

Conference papers

1. **H. Zhang** et al. Helical long period grating in multicore fiber for simultaneous measurement of torsion and temperature. In *CLEO-PR/OECC/PGC*, Aug. 2017.
2. **H. Zhang** et al. Directional bending sensor based on spatially arrayed long period gratings in multicore fiber. In *CLEO-PR/OECC/PGC*, Aug. 2017.
3. **H. Zhang** et al. Simultaneous measurement of torsion and temperature based on helical structure in multicore fiber. In *ACP*, Nov. 2016, Paper AF3A-4. (OSA Best Student Paper Award)

4. **H. Zhang** *et al.* Highly sensitive strain sensor based on helical structure in multicore fiber. In *CLEO*, Jul. 2016, Paper SM2P.3.
5. **H. Zhang** *et al.* Simultaneous measurement of temperature and curvature with multicore fiber based Mach-Zehnder interferometer and fiber Bragg grating, in *PGC*, Jun. 2015.

Bibliography

1. J. Hecht, *City of light: the story of fiber optics* (Oxford University Press on Demand, 2004).
2. A. C. S. Vanheul, "A New Method of Transporting Optical Images without Aberrations," *Nature* **173**, 39-39 (1954).
3. H. H. Hopkins and N. S. Kapany, "A Flexible Fibrescope, Using Static Scanning," *Nature* **173**, 39-41 (1954).
4. E. Snitzer, "Cylindrical Dielectric Waveguide Modes," *J. Opt. Soc. Am.* **51**, 491-498 (1961).
5. K. Kao and G. A. Hockham, "Dielectric-fibre surface waveguides for optical frequencies," in *Proceedings of the Institution of Electrical Engineers*, (IET, 1966), 1151-1158.
6. D. B. Keck, "Optical fiber spans 30 years," *Lightwave* **17**, 78-82 (2000).
7. T. Miya, Y. Terunuma, T. Hosaka, and T. Miyashita, "Ultimate low-loss single-mode fibre at 1.55 μm ," *Electron. Lett.* **15**, 106-108 (1979).
8. M. N. Zervas and C. A. Codemard, "High Power Fiber Lasers: A Review," *IEEE J. Sel. Top Quant. Electron.* **20**, 219-241(2014).
9. K. T. V. Grattan and T. Sun, "Fiber optic sensor technology: an overview," *Sens. Actuators A:Phys.* **82**, 40-61 (2000).
10. R. Ramaswami, "Optical fiber communication: From transmission to networking," *IEEE Commun. Mag.* **40**, 138-147 (2002).
11. F. Mitschke, *Fiber optics: physics and technology* (Springer, 2016).
12. J. L. Kou, J. Feng, L. Ye, F. Xu, and Y. Q. Lu, "Miniaturized fiber taper reflective interferometer for high temperature measurement," *Opt. Express* **18**, 14245-14250 (2010).
13. J. Mathew, Y. Semenova, and G. Farrell, "Effect of coating thickness on the sensitivity of a humidity sensor based on an Agarose coated photonic crystal fiber interferometer," *Opt. Express* **21**, 6313-6320 (2013).

14. J. Villatoro, V. Finazzi, V. P. Minkovich, V. Pruneri, and G. Badenes, "Temperature-insensitive photonic crystal fiber interferometer for absolute strain sensing," *Appl. Phys. Lett.* **91**(2007).
15. C. Y. Lin, L. A. Wang, and G. W. Chern, "Corrugated long-period fiber gratings as strain, torsion, and bending sensors," *J. Lightwave Technol.* **19**, 1159-1168 (2001).
16. H. J. He, L. Y. Shao, B. Luo, Z. L. Li, X. H. Zou, Z. Y. Zhang, W. Pan, and L. S. Yan, "Multiple vibrations measurement using phase-sensitive OTDR merged with Mach-Zehnder interferometer based on frequency division multiplexing," *Opt. Express* **24**, 4842-4855 (2016).
17. B. Xu, C. Wang, D. N. Wang, Y. M. Liu, and Y. Li, "Fiber-tip gas pressure sensor based on dual capillaries," *Opt. Express* **23**, 23484-23492 (2015).
18. Y. Ma, X. Qiao, T. Guo, R. Wang, J. Zhang, Y. Weng, Q. Rong, M. Hu, and Z. Feng, "Mach-Zehnder interferometer based on a sandwich fiber structure for refractive index measurement," *IEEE Sens. J.* **12**, 2081-2085 (2012).
19. J. Villatoro and D. Monzón-Hernández, "Low-cost optical fiber refractive-index sensor based on core diameter mismatch," *J. Lightwave Technol.* **24**, 1409 (2006).
20. L. C. Li, L. Xia, Z. H. Xie, and D. M. Liu, "All-fiber Mach-Zehnder interferometers for sensing applications," *Opt. Express* **20**, 11109-11120 (2012).
21. G. Liu, Q. Sheng, W. Hou, and M. Han, "Optical fiber vector flow sensor based on a silicon Fabry-Perot interferometer array," *Opt. Lett.* **41**, 4629-4632 (2016).
22. R. I. Laming and D. N. Payne, "Electric-Current Sensors Employing Spun Highly Birefringent Optical Fibers," *J. Lightwave Technol.* **7**, 2084-2094 (1989).
23. Y. F. Chen, Q. Han, T. G. Liu, X. W. Lan, and H. Xiao, "Optical fiber magnetic field sensor based on single-mode-multimode-single-mode structure and magnetic fluid," *Opt. Lett.* **38**, 3999-4001 (2013).
24. A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," *IEEE Commun. Surv. Tut.* **17**, 2347-2376 (2015).

25. D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nature Photonics* **7**, 354-362 (2013).
26. R.-J. Essiambre and R. W. Tkach, "Capacity trends and limits of optical communication networks," *Proceedings of the IEEE* **100**, 1035-1055 (2012).
27. S. Iano, T. Sato, S. Sentsui, T. Kuroha, and Y. Nishimura, "Multicore optical fiber," in *Optical Fiber Communication Conference*, (Optical Society of America, 1979), WB1.
28. S. Berdagué and P. Facq, "Mode division multiplexing in optical fibers," *Appl. Opt.* **21**, 1950-1955 (1982).
29. K. Saitoh and S. Matsuo, "Multicore Fiber Technology," *J. Lightwave Technol.* **34**, 55-66 (2016).
30. R. Van Uden, R. A. Correa, E. A. Lopez, F. Huijskens, C. Xia, G. Li, A. Schülzgen, H. De Waardt, A. Koonen, and C. Okonkwo, "Ultra-high-density spatial division multiplexing with a few-mode multicore fibre," *Nature Photonics* **8**, 865 (2014).
31. T. Mizuno, H. Takara, A. Sano, and Y. Miyamoto, "Dense space-division multiplexed transmission systems using multi-core and multi-mode fiber," *J. Lightwave Technol.* **34**, 582-592 (2016).
32. C. Xia, R. Amezcua-Correa, N. Bai, E. Antonio-Lopez, D. M. Arriola, A. Schulzgen, M. Richardson, J. Liñares, C. Montero, and E. Mateo, "Hole-assisted few-mode multicore fiber for high-density space-division multiplexing," *IEEE Photonic Tech. Lett.* **24**, 1914-1917 (2012).
33. H. J. Patrick, G. M. Williams, A. D. Kersey, J. R. Pedrazzani, and A. M. Vengsarkar, "Hybrid fiber Bragg grating/long period fiber grating sensor for strain/temperature discrimination," *IEEE Photonic Tech. Lett.* **8**, 1223-1225 (1996).
34. S. W. James, M. L. Dockney, and R. P. Tatam, "Simultaneous independent temperature and strain measurement using in-fibre Bragg grating sensors," *Electron. Lett.* **32**, 1133-1134 (1996).
35. M. G. Xu, J. L. Archambault, L. Reekie, and J. P. Dakin, "Discrimination between Strain and Temperature Effects Using Dual-Wavelength Fiber Grating Sensors," *Electron. Lett.* **30**, 1085-1087 (1994).

36. T. Erdogan, "Fiber grating spectra," J. Lightwave Technol. **15**, 1277-1294 (1997).
37. I. R. Ivascu, R. Gumenyuk, S. Kivisto, and O. G. Okhotnikov, "Fabrication of high reflectivity chirped fiber Bragg gratings and its sensing applications," Optoelectron. Adv. Mat. **5**, 911-915 (2011).
38. M. M. Werneck, R. C. Allil, B. A. Ribeiro, and F. V. de Nazaré, "A guide to fiber Bragg grating sensors," in *Current Trends in Short-and Long-period Fiber Gratings* (InTech, 2013).
39. R. Kashyap, *Fiber bragg gratings* (Academic press, 2009).
40. A. M. Smith, "Birefringence induced by bends and twists in single-mode optical fiber," Appl. Opt. **19**, 2606-2611 (1980).
41. A. Taghipour, A. Rostami, M. Bahrami, H. Baghban, and M. Dolatyari, "Comparative study between LPFG- and FBG-based bending sensors," Opt. Commun. **312**, 99-105 (2014).
42. S. Makouei and F. Makouei, "Strain Effect Study on Mode Field Diameter and Effective Area of WII Type Single Mode Optical Fiber," Advanced Electromagnetics **5**, 53-61 (2016).
43. I. Abdulhalim and C. N. Pannell, "Photoelastic in-fiber birefringence modulator operating at the fundamental transverse acoustic resonance," IEEE Photonic Tech. Lett. **5**, 1197-1199 (1993).
44. E. Li, "Temperature compensation of multimode-interference-based fiber devices," Opt. Lett. **32**, 2064-2066 (2007).
45. S. Magne, S. Rougeault, M. Vilela, and P. Ferdinand, "State-of-strain evaluation with fiber Bragg grating rosettes: application to discrimination between strain and temperature effects in fiber sensors," Appl. Opt. **36**, 9437-9447 (1997).
46. Y. J. Rao, "In-fibre Bragg grating sensors," Measurement Science and Technology **8**, 355 (1997).
47. Y. P. Wang, H. Bartelt, W. Ecke, R. Wilisch, J. Kobelke, M. Kautz, S. Brueckner, and M. Rothhardt, "Sensing properties of fiber Bragg gratings in small-core Ge-doped photonic crystal fibers," Opt. Commun. **282**, 1129-1134 (2009).

48. M. J. Gander, W. N. MacPherson, R. McBride, J. D. C. Jones, L. Zhang, I. Bennion, P. M. Blanchard, J. G. Burnett, and A. H. Greenaway, "Bend measurement using Bragg gratings in multicore fibre," *Electron. Lett.* **36**, 120-121 (2000).
49. G. Meltz, W. W. Morey, and W. H. Glenn, "Formation of Bragg Gratings in Optical Fibers by a Transverse Holographic Method," *Opt. Lett.* **14**, 823-825 (1989).
50. G. M. H. Flockhart, W. N. MacPherson, J. S. Barton, J. D. C. Jones, L. Zhang, and I. Bennion, "Two-axis bend measurement with Bragg gratings in multicore optical fiber," *Opt. Lett.* **28**, 387-389 (2003).
51. J. P. Moore and M. D. Rogge, "Shape sensing using multi-core fiber optic cable and parametric curve solutions," *Opt. Express* **20**, 2967-2973 (2012).
52. C. G. Askins, G. A. Miller, and E. J. Friebele, "Bend and twist sensing in a multiple-core optical fiber," in *Optical Fiber Communication Conference*, (Optical Society of America, 2008), OMT3.
53. D. Barrera, I. Gasulla, and S. Sales, "Multipoint Two-Dimensional Curvature Optical Fiber Sensor Based on a Nontwisted Homogeneous Four-Core Fiber," *J. Lightwave Technol.* **33**, 2445-2450 (2015).
54. D. Barrera, I. Gasulla, and S. Sales, "Non-uniform shape sensor based on FBGs inscribed in multicore optical fibers," in *Optical Sensors*, (Optical Society of America, 2014), SeW2C. 5.
55. P. S. Westbrook, K. S. Feder, T. Kremp, T. F. Taunay, E. Monberg, J. Kelliher, R. Ortiz, K. Bradley, K. S. Abedin, D. Au, and G. Puc, "Integrated optical fiber shape sensor modules based on twisted multicore fiber grating arrays," in *SPIE BiOS*, (International Society for Optics and Photonics, 2014), 89380H-89380H-89387.
56. T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," *Opt. Express* **19**, 16576-16592 (2011).
57. X. W. Shu, L. Zhang, and I. Bennion, "Sensitivity characteristics of long-period fiber gratings," *J. Lightwave Technol.* **20**, 255-266 (2002).

58. A. Iadicicco and S. Campopiano, "Sensing Features of Long Period Gratings in Hollow Core Fibers," *Sensors* **15**, 8009-8019 (2015).
59. R. Wang, M. Tang, S. Fu, Z. Feng, W. Tong, and D. Liu, "Spatially Arrayed Long Period Gratings in Multicore Fiber by Programmable Electrical Arc Discharge," *IEEE Photonics J.* **9**, 1-10 (2017).
60. D. Barrera, J. Madrigal, and S. Sales, "Long Period Gratings in Multicore Optical Fibers for Directional Curvature Sensor Implementation," *J. Lightwave Technol.* **36**, 1063-1068 (2018).
61. J. H. Liou and C. P. Yu, "All-fiber Mach-Zehnder interferometer based on two liquid infiltrations in a photonic crystal fiber," *Opt. Express* **23**, 6946-6951 (2015).
62. B. H. Lee, Y. H. Kim, K. S. Park, J. B. Eom, M. J. Kim, B. S. Rho, and H. Y. Choi, "Interferometric Fiber Optic Sensors," *Sensors* **12**, 2467-2486 (2012).
63. J. Zhou, C. Liao, Y. Wang, G. Yin, X. Zhong, K. Yang, B. Sun, G. Wang, and Z. Li, "Simultaneous measurement of strain and temperature by employing fiber Mach-Zehnder interferometer," *Opt. Express* **22**, 1680-1686 (2014).
64. S. Feng, H. Li, O. Xu, S. Lu, and S. Jian, "Compact in-fiber Mach-Zehnder interferometer using a twin-core fiber," in *Communications and Photonics Conference and Exhibition (ACP), 2009 Asia*, (IEEE, 2009), 1-5.
65. C. Li, T. Ning, J. Li, C. Zhang, C. Zhang, H. Lin, and L. Pei, "Fiber-optic laser sensor based on all-fiber multipath Mach-Zehnder interferometer," *IEEE Photonic Tech. Lett.* **28**, 1908-1911 (2016).
66. A. Van Newkirk, J. E. Antonio-Lopez, G. Salceda-Delgado, M. U. Piracha, R. Amezcua-Correa, and A. Schulzgen, "Multicore Fiber Sensors for Simultaneous Measurement of Force and Temperature," *IEEE Photonic Tech. Lett.* **27**, 1523-1526 (2015).
67. J. E. Antonio Lopez, Z. Eznavah, P. LiKamWa, A. Schuelzgen, and R. Amezcua Correa, "Multicore fiber sensor for high-temperature applications up to 1000 °C," *Opt. Lett.* **39**, 4309-4312 (2014).
68. G. Salceda-Delgado, A. Van Newkirk, J. E. Antonio-Lopez, A. Martinez-Rios, A. Schulzgen, and R. A. Correa, "Compact fiber-optic curvature sensor based

- on super-mode interference in a seven-core fiber," *Opt. Lett.* **40**, 1468-1471 (2015).
69. J. Villatoro, E. Antonio-Lopez, J. Zubia, A. Schlzgen, and R. Amezcua-Correa, "Interferometer based on strongly coupled multi-core optical fiber for accurate vibration sensing," *Opt. Express* **25**, 25734-25740 (2017).
 70. Z. Y. Zhao, M. Tang, S. N. Fu, S. Liu, H. F. Wei, Y. Cheng, W. J. Tong, P. Shum, and D. M. Liu, "All-solid multi-core fiber-based multipath Mach-Zehnder interferometer for temperature sensing," *Appl. Phys. B* **112**, 491-497 (2013).
 71. L. Gan, R. X. Wang, D. M. Liu, L. Duan, S. Liu, S. N. A. Fu, B. R. Li, Z. H. Feng, H. F. Wei, W. J. Tong, P. Shum, and M. Tang, "Spatial-Division Multiplexed Mach-Zehnder Interferometers in Heterogeneous Multicore Fiber for Multiparameter Measurement," *IEEE Photon. J.* **8**(2016).
 72. X. Wang, D. Chen, H. Li, G. Feng, and J. Yang, "In-line Mach-Zehnder interferometric sensor based on a seven-core optical fiber," *IEEE Sens. J.* **17**, 100-104 (2017).
 73. J. Y. Yang, Y. Z. Zheng, L. H. Chen, C. C. Chan, X. Y. Dong, P. P. Shum, and H. B. Su, "Miniature temperature sensor with germania-core optical fiber," *Opt. Express* **23**, 17687-17692 (2015).
 74. L. Duan, P. Zhang, M. Tang, R. X. Wang, Z. Y. Zhao, S. N. Fu, L. Gan, B. P. Zhu, W. J. Tong, D. M. Liu, and P. P. Shum, "Heterogeneous all-solid multicore fiber based multipath Michelson interferometer for high temperature sensing," *Opt. Express* **24**, 20210-20218 (2016).
 75. J. Villatoro, O. Arrizabalaga, G. Durana, I. S. de Ocariz, E. Antonio-Lopez, J. Zubia, A. Schulzgen, and R. Amezcua-Correa, "Accurate strain sensing based on super-mode interference in strongly coupled multi-core optical fibres," *Sci. Rep.* **7**, 4451 (2017).
 76. J. Villatoro, E. Antonio-Lopez, A. Schulzgen, and R. Amezcua-Correa, "Miniature multicore optical fiber vibration sensor," *Opt. Lett.* **42**, 2022-2025 (2017).
 77. K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *J. Lightwave Technol.* **15**, 1263-1276 (1997).

78. R. H. Wang and X. G. Qiao, "Intrinsic Fabry-Perot Interferometric Sensor Based on Microfiber Created by Chemical Etching," *Sensors* **14**, 16808-16815 (2014).
79. G. K. B. Costa, P. M. P. Gouvêa, L. M. B. Soares, J. M. B. Pereira, F. Favero, A. M. B. Braga, P. Palffy-Muhoray, A. C. Bruno, and I. C. S. Carvalho, "In-fiber Fabry-Perot interferometer for strain and magnetic field sensing," *Opt. Express* **24**, 14690-14696 (2016).
80. Y.J. Rao, M. Deng, D.-W. Duan, and T. Zhu, "In-line fiber Fabry-Perot refractive-index tip sensor based on endlessly photonic crystal fiber," *Sens. and Actuators A: Physical* **148**, 33-38 (2008).
81. J. Kong, A. Zhou, and L. Yuan, "Temperature insensitive one-dimensional bending vector sensor based on eccentric-core fiber and air cavity Fabry-Perot interferometer," *J. of Opt.* **19**, 045705 (2017).
82. X. Zhang, L. Shao, X. Zou, B. Luo, W. Pan, and L. Yan, "Chirped fiber tip Fabry-Perot interferometer," *Opt. Lett.* **42**, 3474-3477 (2017).
83. Y. Zhang, Y. Zhang, Z. Wang, Z. Liu, Y. Wei, E. Zhao, X. Yang, J. Zhang, J. Yang, and L. Yuan, "A novel Michelson Fabry-Perot hybrid interference sensor based on the micro-structured fiber," *Opt. Commun.* **374**, 58-63 (2016).
84. Y. Ouyang, H. Guo, X. Ouyang, Y. Zhao, Z. Zheng, C. Zhou, and A. Zhou, "An In-Fiber Dual Air-Cavity Fabry-Perot Interferometer for Simultaneous Measurement of Strain and Directional Bend," *IEEE Sens. J.* **17**, 3362-3366 (2017).
85. H. L. Zhang, Z. F. Wu, P. P. Shum, R. X. Wang, X. Q. Dinh, S. N. Fu, W. J. Tong, and M. Tang, "Fiber Bragg gratings in heterogeneous multicore fiber for directional bending sensing," *J. of Opt.* **18**(2016).
86. C. G. Askins, T. F. Taunay, G. A. Miller, B. M. Wright, J. R. Peele, L. R. Wasserman, and E. J. Friebele, "Inscription of fiber Bragg gratings in multicore fiber," in *Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, (Optical Society of America, 2007), JWA39.
87. J. Bland-Hawthorn, S. C. Ellis, S. G. Leon-Saval, R. Haynes, M. M. Roth, H. G. Lohmannsroben, A. J. Horton, J. G. Cuby, T. A. Birks, J. S. Lawrence, P.

- Gillingham, S. D. Ryder, and C. Trinh, "A complex multi-notch astronomical filter to suppress the bright infrared sky," *Nature commun.* **2**(2011).
88. S. S. Min, C. Trinh, S. Leon-Saval, N. Jovanovic, P. Gillingham, J. Bland-Hawthorn, J. Lawrence, T. A. Birks, M. M. Roth, R. Haynes, and L. Fogarty, "Multicore fibre Bragg grating developments for OH suppression," *Proc. SPIE* **2012**, 8450 (2012).
 89. E. Lindley, S. S. Min, S. Leon-Saval, N. Cvetojevic, J. Lawrence, S. Ellis, and J. Bland-Hawthorn, "Demonstration of uniform multicore fiber Bragg gratings," *Opt. Express* **22**, 31575-31581 (2014).
 90. P. S. Westbrook, K. S. Abedin, T. F. Taunay, T. Kremp, J. Porque, E. Monberg, and M. Fishteyn, "Multicore fiber distributed feedback lasers," *Opt. Lett.* **37**, 4014-4016 (2012).
 91. B. Li, Z. Feng, M. Tang, Z. Xu, S. Fu, Q. Wu, L. Deng, W. Tong, S. Liu, and P. P. Shum, "Experimental demonstration of large capacity WSDM optical access network with multicore fibers and advanced modulation formats," *Opt. Express* **23**, 10997-11006 (2015).
 92. Z. Feng, B. Li, M. Tang, L. Gan, R. Wang, R. Lin, Z. Xu, S. Fu, L. Deng, W. Tong, S. Long, L. Zhang, H. Zhou, R. Zhang, S. Liu, and P. P. Shum, "Multicore-Fiber-Enabled WSDM Optical Access Network With Centralized Carrier Delivery and RSOA-Based Adaptive Modulation," *IEEE Photon. J.* **7**, 1-9 (2015).
 93. Z. Zhao, M. Tang, S. Fu, S. Liu, H. Wei, Y. Cheng, W. Tong, P. P. Shum, and D. Liu, "All-solid multi-core fiber-based multipath Mach–Zehnder interferometer for temperature sensing," *Appl. Phys. B* **112**, 491-497 (2013).
 94. I. Malitson, "Interspecimen comparison of the refractive index of fused silica," *Josa* **55**, 1205-1209 (1965).
 95. V. Brückner, "To the use of Sellmeier formula," Senior Experten Service (SES) Bonn and HfT Leipzig, Germany (2011).
 96. M. M, R. C. S. B. Allil, B. A, and F. V. B. de Nazar, "A Guide to Fiber Bragg Grating Sensors," In *Current Trends in Short-and Long-period Fiber Gratings* Intech, (2013).

97. I. Bennion, J. A. R. Williams, L. Zhang, K. Sugden, and N. J. Doran, "UV-written in-fibre Bragg gratings," *Opt. Quant. Electron.* **28**, 93-135 (1996).
98. C. C. Ye, S. W. James, and R. P. Tatam, "Simultaneous temperature and bend sensing with long-period fiber gratings," *Opt. Lett.* **25**, 1007-1009 (2000).
99. Z. Wenjun, Z. Yan, D. Xinyong, S. Li-Yang, C. Jia, and J. Albert, "Fiber-Optic Curvature Sensor Based on Cladding-Mode Bragg Grating Excited by Fiber Multimode Interferometer," *IEEE Photon. J.* **4**, 1051-1057 (2012).
100. C. Gouveia, P. Jorge, J. Baptista, and O. Frazao, "Temperature-independent curvature sensor using FBG cladding modes based on a core misaligned splice," *IEEE Photon. Technol. Lett.* **23**, 804-806 (2011).
101. A. Martinez, Y. Lai, M. Dubov, I. Y. Khrushchev, and I. Bennion, "Vector bending sensors based on fiber Bragg gratings inscribed by an infrared femtosecond laser," in *Conference on Lasers and Electro-Optics*, (Optical Society of America, 2005), CFH1.
102. X. F. Chen, C. Zhang, D. Webb, K. Kalli, and P. Gang-Ding, "Highly sensitive bend sensor based on Bragg grating in eccentric core polymer fiber," *IEEE Photon. Tech. Lett.* **22**(2010).
103. Z. Wu, Y.G. Liu, Z. Wang, T. Han, S. Li, M. Jiang, P. P. Shum, and X. Q. Dinh, "In-line Mach-Zehnder interferometer composed of microtaper and long-period grating in all-solid photonic bandgap fiber," *Appl. Phys. Lett.* **101**, 141106 (2012).
104. Z. Wu, Y. G. Liu, Z. Wang, M. Jiang, W. Ji, T. Han, S. Li, X. Shao, X. Q. Dinh, S. C. Tjin, and P. P. Shum, " Simultaneous measurement of curvature and strain based on fiber Bragg grating in two-dimensional waveguide array fiber," *Opt. Lett.* **38**, 4070-4073 (2013).
105. H. Zhang, Z. Wu, P. P. Shum, X. Q. Dinh, C. W. Low, Z. Xu, R. Wang, X. Shao, S. Fu, W. Tong, and M. Tang, "Highly sensitive strain sensor based on helical structure combined with Mach-Zehnder interferometer in multicore fiber," *Sci. Rep.* **7**, 46633 (2017).
106. Z. F. Wu, H. L. Zhang, P. P. Shum, X. G. Shao, T. Y. Huang, Y. M. Seow, Y. G. Liu, H. F. Wei, and Z. Wang, "Supermode Bragg grating combined Mach-

- Zehnder interferometer for temperature-strain discrimination," *Opt. Express* **23**, 33001-33007 (2015).
107. Y. P. Wang, L. M. Xiao, D. N. Wang, and W. Jin, "Highly sensitive long-period fiber-grating strain sensor with low temperature sensitivity," *Opt. Lett.* **31**, 3414-3416 (2006).
 108. R. Wang, L. Duan, M. Tang, S. Fu, P. Zhang, Z. Feng, L. Borui, T. Weijun, D. Liu, and P. P. Shum, "Long Period Grating in Multicore Fiber and Its Application for Measurement of Temperature and Strain," in *Asia Communications and Photonics Conference*, (Optical Society of America, 2015), AM1D. 5.
 109. C. R. Liao, D. N. Wang, and Y. Wang, "Microfiber in-line Mach-Zehnder interferometer for strain sensing," *Opt. Lett.* **38**, 757-759 (2013).
 110. J. Villatoro, V. Finazzi, G. Coviello, and V. Pruneri, "Photonic-crystal-fiber-enabled micro-Fabry-Perot interferometer," *Opt. Lett.* **34**, 2441-2443 (2009).
 111. D. W. Duan, Y. J. Rao, Y. S. Hou, and T. Zhu, "Microbubble based fiber-optic Fabry-Perot interferometer formed by fusion splicing single-mode fibers for strain measurement," *Appl. Opt.* **51**, 1033-1036 (2012).
 112. M. S. Ferreira, J. Bierlich, J. Kobelke, K. Schuster, J. L. Santos, and O. Frazão, "Towards the control of highly sensitive Fabry-Pérot strain sensor based on hollow-core ring photonic crystal fiber," *Opt. Express* **20**, 21946-21952 (2012).
 113. S. Liu, K. M. Yang, Y. P. Wang, J. L. Qu, C. R. Liao, J. He, Z. Y. Li, G. L. Yin, B. Sun, J. T. Zhou, G. J. Wang, J. Tang, and J. Zhao, "High-sensitivity strain sensor based on in-fiber rectangular air bubble," *Sci. Rep.* **5**, 7624 (2015).
 114. P. Zhang, M. Tang, F. Gao, B. Zhu, S. Fu, J. Ouyang, P. P. Shum, and D. Liu, "Cascaded fiber-optic Fabry-Perot interferometers with Vernier effect for highly sensitive measurement of axial strain and magnetic field," *Opt. Express* **22**, 19581-19588 (2014).
 115. V. I. Kopp, J. Park, M. Wlodawski, J. Singer, D. Neugroschl, and A. Z. Genack, "Chiral fibers: microformed optical waveguides for polarization control, sensing, coupling, amplification, and switching," *J. Lightwave Technol.* **32**, 605-613 (2014).

116. V. I. Kopp, V. M. Churikov, J. Singer, N. Chao, D. Neugroschl, and A. Z. Genack, "Chiral fiber gratings," *Science* **305**, 74-75 (2004).
117. V. I. Kopp, V. M. Churikov, G. Zhang, J. Singer, C. W. Draper, N. Chao, D. Neugroschl, and A. Z. Genack, "Single- and double-helix chiral fiber sensors," *J. Opt. Soc. Am. B* **24**, A48-A52 (2007).
118. V. I. Kopp and A. Z. Genack, "Chiral Fibres Adding Twist," *Nature Photonics* **5**, 470-472 (2011).
119. J. Park, M. S. Wlodawski, J. Singer, D. Neugroschl, A. Z. Genack, and V. I. Kopp, "Temperature and pressure sensors based on chiral fibers," in *SPIE Defense, Security, and Sensing*, (International Society for Optics and Photonics, 2012), 837008-837008-837008.
120. G. K. L. Wong, M. S. Kang, H. W. Lee, F. Biancalana, C. Conti, T. Weiss, and P. S. Russell, "Excitation of Orbital Angular Momentum Resonances in Helically Twisted Photonic Crystal Fiber," *Science* **337**, 446-449 (2012).
121. X. M. Xi, G. K. L. Wong, T. Weiss, and P. S. Russell, "Measuring mechanical strain and twist using helical photonic crystal fiber," *Opt. Lett.* **38**, 5401-5404 (2013).
122. Z. L. Xu, Q. Z. Sun, J. H. Wo, Y. Dai, X. L. Li, and D. M. Liu, "Volume Strain Sensor Based on Spectra Analysis of In-Fiber Modal Interferometer," *IEEE Sens. J.* **13**, 2139-2145 (2013).
123. L. V. Nguyen, D. Hwang, S. Moon, D. S. Moon, and Y. J. Chung, "High temperature fiber sensor with high sensitivity based on core diameter mismatch," *Opt. Express* **16**, 11369-11375 (2008).
124. D. Wu, T. Zhu, K. S. Chiang, and M. Deng, "All Single-Mode Fiber Mach-Zehnder Interferometer Based on Two Peanut-Shape Structures," *J. Lightwave Technol.* **30**, 805-810 (2012).
125. H. F. Chen, D. N. Wang, and Y. Wang, "Simultaneous strain and temperature sensing using a slightly tapered optical fiber with an inner cavity," *Analyst* **140**, 1859-1862 (2015).
126. P. Lu and Q. Chen, "Asymmetrical fiber Mach-Zehnder interferometer for simultaneous measurement of axial strain and temperature," *IEEE Photon. J.* **2**, 942-953 (2010).

127. H. F. Chen, D. N. Wang, and W. Hong, "Slightly Tapered Optical Fiber With Inner Air-Cavity as a Miniature and Versatile Sensing Device," *J. Lightwave Technol.* **33**, 62-68 (2015).
128. H. L. Zhang, M. Tang, Y. W. Xie, H. Q. Liao, S. N. Fu, P. Shum, and D. M. Liu, "Programmable all-fiber structured waveshaper based on linearly chirped fiber Bragg grating and digital thermal controller," *Appl. Phys. B* **112**, 479-484 (2013).
129. P. Lu, L. Q. Men, K. Sooley, and Q. Y. Chen, "Tapered fiber Mach-Zehnder interferometer for simultaneous measurement of refractive index and temperature," *Appl. Phys. Lett.* **94**(2009).
130. H. Y. Choi, M. J. Kim, and B. H. Lee, "All-fiber Mach-Zehnder type interferometers formed in photonic crystal fiber," *Opt. Express* **15**, 5711-5720 (2007).
131. H. L. Zhang, Z. F. Wu, P. P. Shum, X. G. Shao, R. X. Wang, X. Q. Dinh, S. N. Fu, W. J. Tong, and M. Tang, "Directional torsion and temperature discrimination based on a multicore fiber with a helical structure," *Opt. Express* **26**, 544-551 (2018).
132. G. Wang, K. Pran, G. Sagvolden, G. B. Havsgard, A. E. Jensen, G. A. Johnson, and S. T. Vohra, "Ship hull structure monitoring using fibre optic sensors," *Smart Mater. Struct.* **10**, 472-478 (2001).
133. R. Xu, A. Yurkewich, and R. V. Patel, "Curvature, torsion, and force sensing in continuum robots using helically wrapped FBG sensors," *IEEE Robot. and Automat. Lett.* **1**, 1052-1059 (2016).
134. H. M. Kim, T. H. Kim, B. Kim, and Y. Chung, "Temperature-Insensitive Torsion Sensor With Enhanced Sensitivity by Use of a Highly Birefringent Photonic Crystal Fiber," *IEEE Photonic Tech L* **22**, 1539-1541 (2010).
135. W. G. Chen, S. Q. Lou, L. W. Wang, H. Zou, W. L. Lu, and S. S. Jian, "Highly Sensitive Torsion Sensor Based on Sagnac Interferometer Using Side-Leakage Photonic Crystal Fiber," *IEEE Photonic Tech. Lett.* **23**, 1639-1641 (2011).
136. Y. Wang and Y. Rao, "Long period fibre grating torsion sensor measuring twist rate and determining twist direction simultaneously," *Electron. Lett.* **40**, 164-166 (2004).

137. B. Huang and X. W. Shu, "Ultra-compact strain- and temperature-insensitive torsion sensor based on a line-by-line inscribed phase-shifted FBG," *Opt. Express* **24**, 17670-17679 (2016).
138. N. K. Chen, J. J. Wang, G. L. Cheng, W. H. Cheng, and P. P. Shum, "Fiber torsion sensor with directional discrimination based on twist-induced circular birefringence in unbalanced Mach-Zehnder interferometer," in *CLEO: 2014*, OSA Technical Digest (online) (Optical Society of America, 2014), JW2A.35.
139. Q. Zhou, W. G. Zhang, L. Chen, T. Y. Yan, L. Y. Zhang, L. Wang, and B. Wang, "Fiber torsion sensor based on a twist taper in polarization-maintaining fiber," *Opt. Express* **23**, 23877-23886 (2015).
140. L. Zhang, Y. Q. Liu, X. B. Cao, and T. Y. Wang, "High Sensitivity Chiral Long-Period Grating Sensors Written in the Twisted Fiber," *IEEE Sens. J.* **16**, 4253-4257 (2016).
141. L. L. Xian, P. Wang, and H. P. Li, "Power-interrogated and simultaneous measurement of temperature and torsion using paired helical long-period fiber gratings with opposite helicities," *Opt. Express* **22**, 20260-20267 (2014).
142. L. A. Fernandes, J. R. Grenier, J. S. Aitchison, and P. R. Herman, "Fiber optic stress-independent helical torsion sensor," *Optics Letters* **40**, 657-660 (2015).
143. P. S. J. Russell, R. Beravat, and G. K. L. Wong, "Helically twisted photonic crystal fibres," *Phil. Trans. R. Soc. A* **375** (2017).
144. X. Q. Ma, C. H. Liu, G. Q. Chang, and A. Galvanauskas, "Angular-momentum coupled optical waves in chirally-coupled-core fibers," *Opt. Express* **19**, 26515-26528 (2011).
145. L. L. Shi, T. Zhu, Y. E. Fan, K. S. Chiang, and Y. J. Rao, "Torsion sensing with a fiber ring laser incorporating a pair of rotary long-period fiber gratings," *Opt. Commun.s* **284**, 5299-5302 (2011).
146. Y. O. Agha, F. Zolla, A. Nicolet, and S. Guenneau, "On the use of PML for the computation of leaky modes - An application to microstructured optical fibres," *Compel* **27**, 95-109 (2008).
147. Y. P. Wang, J. P. Chen, and Y. J. Rao, "Torsion characteristics of long-period fiber gratings induced by high-frequency CO₂ laser pulses," *J. Opt. Soc. Am. B* **22**, 1167-1172 (2005).

148. C. Li, T. A. Ning, C. Zhang, J. Li, C. B. Zhang, X. D. Wen, H. Lin, and L. Pei, "All-fiber multipath Mach-Zehnder interferometer based on a four-core fiber for sensing applications," *Sens. Actuat. A: Phys.* **248**, 148-154 (2016).
149. K. K. Lee, A. Mariampillai, M. Haque, B. A. Standish, V. X. Yang, and P. R. Herman, "Temperature-compensated fiber-optic 3D shape sensor based on femtosecond laser direct-written Bragg grating waveguides," *Opt. Express*, **21**(20), 24076-24086 (2013).