Design and analysis of photonic crystal fiber based devices for optical communication systems

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Design and Analysis of Photonic Crystal Fiber based Devices for Optical Communication Systems

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Summary

Photonic crystal fiber (PCF) has been studied intensively in the past decade owing to its potential device applications in optical communication systems. PCFs have many advantages compared with the conventional fibers. Firstly, they have flexibly-tailored optical properties. Due to the microstructure dependence of their modal properties, the degree of freedom is increased dramatically in the design. Many properties such as the cutoff conditions, birefringence, dispersion and nonlinearity can be tailored beyond the possibilities in conventional fibers. Moreover, because of the single material in most PCFs, their improved temperature stability makes such novel fiber a suitable transmission medium. Secondly, the unique holey structure makes many applications possible. Due to the special stack-and-draw fabrication technique, the arrangement of air-holes in the microstructure can be customized. Multiple layers of claddings can be easily obtained by controlling the air-hole dimensions of capillary tubes in different layers. Multi-core structures are achieved by simply introducing multiple solid rods during the stacking process. The existence of air-holes enables the possibilities of injecting gases/liquids, so that PCF can be used as sensors.

We analyzed microstructured PCFs and investigated various numerical methods for solving the vector-form wave equations. Beam propagation method and plane wave method are chosen to model the novel structures proposed. Both of these methods are having satisfactory numerical accuracy and computational efficiency. Several new designs are proposed, such as highly-birefringent PCF, dispersion shifting PCF, dispersion compensating PCF and two-core PCF. They can be utilized in polarization maintaining, dispersion tailoring and directional coupling applications, respectively.

We propose and discuss HiBi-PCF with elliptical air-holes. The dependence of birefringence with wavelength, air-filling fraction, and ellipticity is analyzed specifically. The idea of elliptical lattice is further extended to HiBi-PCF based on bandgap-guiding. The high-index rods in the cladding are elliptical in shape and isolated in another solid material of low-index. Structures with birefringence value as large as 10^{-3} are obtained, which is found to be more effective than conventional HiBi fibers for polarization maintaining applications. Besides the theoretical studies, a single material HiBi-PCF is deployed into a fiber laser system to effectively improve the temperature stability as a birefringent component. The thermal coefficient of the lasing wavelength is found to have a ten times improvement compared with using conventional HiBi fiber.

To design new structures for dispersion tailoring, we carry out the modeling of standard PCF, interstitial-hole assistant PCF and concentric-core PCF. A significant shift of the zero dispersion wavelengths is observed with the variations of air-filling fractions. Such fiber components effectively engineer the dispersion in a transmission system. Negative dispersion value as large as -6000ps/km-nm is achieved at 1550nm wavelength. These highly-dispersive structures are important for compensating the dispersion accumulated in optical communication system.

Furthermore, we explore the coupling effects in two-core PCFs. The coupled mode theory and super mode theory are discussed and compared to calculate the coupling coefficient and coupling coefficient dispersion. The dependence of coupling coefficient on geometrical parameters is analyzed in detail, such as air-filling fraction, core-to-core separation, and air-hole arrangement. In order to verify the theoretical

results, two types of two-core PCFs are fabricated which can achieve strong and weak coupling respectively. Experimental work is carried out to measure the coupling coefficient and coupling coefficient dispersion, and the measured results show good agreement with the numerical calculations. The observation and analysis of tradeoff between the coupling coefficient and coupling coefficient dispersion in PCFs provides a useful guideline for designing broadband directional couplers.

To extend the study of mode coupling in PCFs, the properties of PCF based long period gratings (LPGs) and their applications have also been explored. Their fabrication process, unique mode coupling characteristics and applications are investigated both theoretically and experimentally. Two techniques are developed to fabricate PCF based LPGs: point by point stress relaxation method by CO₂ laser, and periodic photoelastic method by mechanical pressure. Resonance notch more than 30dB is achieved by both techniques and their temperature sensitivities are studied experimentally. Taking advantage of the significantly-improved thermal stability of PCF based LPGs, we demonstrate a Mach-Zehnder interferometer based on a grating pair. Alternatively, a single LPG with assistance of a misalignment splicing point is proposed as an interferometer. Moreover, such tunable device is applied to measure the fiber torsion sensitivity.

List of Acronyms

BPM	Beam Propagation Method
CCD	Charge Coupled Device
DC	Dispersion Compensation
DCF	Dispersion Compensating Fiber
DFB	Distributed Feedback
EDF	Erbium Doped Fiber
EDFA	Erbium Doped Fiber Amplifier
EDFL	Erbium Doped Fiber Laser
ESM	Endlessly Single Mode
EH	Elliptical Hole
FBG	Fiber Bragg Grating
FEM	Finite Element Method
FWHM	Full Width Half Maximum
FVFEM	Full-Vector Finite Element Method
GVD	Group Velocity Dispersion
HNA	High Numerical Aperture
HNL	Highly Nonlinear
IH	Interstitial Hole
LMA	Large Mode Area
LPG	Long Period Grating
MLPG	Mechanical Long Period Grating
MSP	Misalignment Splicing Point

MWFL	Multi-Wavelength Fiber Laser
MZI	Mach-Zehnder Interferometer
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
PBG	Photonic Bandgap
PBGF	Photonic Bandgap Fiber
PC	Photonic Crystal
PCF	Photonic Crystal Fiber
PDL	Polarization Dependent Loss
PM	Polarization Maintaining
PMD	Polarization Mode Dispersion
PMF	Polarization Maintaining Fiber
PML	Perfectly Matched Layer
PMMA	Polymethyl Methacrylate
PWM	Plane Wave Method
SAP	Stress Applying Part
SLD	Super Luminescent Diode
SVBPM	Semi-Vector Beam Propagation Method
SMF	Single Mode Fiber
SOP	State of Polarization
WDM	Wavelength Division Multiplexing

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1 Introduction

1.1 Background and Motivations

1.1.1 Historical Overview

It was only about thirty years ago that the low loss optical fibers was realized which made the long haul optical transmission possible [1]. Then a new era of worldwide high speed telecommunication began to reshape the global economy [2]. In the 90s of last century, the incredible growth of data communication demands a huge transmission capability. However, the unavoidable nonlinear effects and the polarization mode dispersion in conventional fibers limit the application for high speed and high density transmission. The dreaming and eagerness of inventing new types of fiber motivated the scientific world.

Actually, back to the early year of 1974, single material fiber has already been proposed by Kaiser *et al.* as a possible approach to low-loss optical fiber [3]. However, it was not able to attract much attention because it did not provide much advantage or tunability compared with conventional step index fiber. But those years in 70s, periodic optical structures such as the thin film filters were intensively under investigation. Until the year 1978, Yeh and Yariv proposed and analyzed for the first

time a Bragg fiber structure [4] and wide single-mode operation was noted at that time. In 1987, S. John and E. Yablonovitch suggested almost at the same time that interesting phenomenon such as spontaneous emission inhibition and photon localization can be achieved if a dielectric function of a material is periodic in every dimension [5]-[6]. Such research work stimulated the designs and applications of photonic bandgap (PBG) structures. In the early 1990s, interest in air-glass fiber profiles was rekindled by the idea of creating two-dimensional PBG in optical fibers. Typically, these optical fibers have a collection of air-holes running along the length of the fiber, and they can be named under a big category of photonic crystal fiber (PCF). Until year 1996, a PCF structure was fabricated by J. C. Knight *et al.* However this first PCF was not able to achieve PBG, rather it was based on a modified guiding mechanism of total internal reflection similar to conventional fiber [7]-[8]. In the year 1999, R. F. Cregan *et al.* fabricated a PCF which guided light by true PBG effect [9]. All the novel and fascinating possibilities offered by PCF in the beginning were all based on the fact that the guidance could be achieved in a hollow core. So that the loss and nonlinearity can be suppressed to extremely low level (only air inside!). But the discovery of a number of interesting physical effects, some not necessarily associated with PBG effect, has blossomed into the popular research field of PCF ever from the last decade. Along with that, a potentially confusing series of names has been developed to distinguish between the various embodiments. Fortunately, the physics describing the fibers conveniently separates them into two distinct classes, those employing PBG for guidance and those with modified total internal reflection for guidance [10]-[11]. Hollow-core PCF and photonic bandgap fiber (PBGF) refer to those fiber structures using bandgap-guiding mechanism. The terms holey fiber, hole-assisted fiber, are referring to fibers that employ index-guiding mechanism. In this

thesis, PBGF is used for bandgap structures. Unless specially specified, the term PCF in this thesis is used for the group of index-guiding because: though not all of the fiber profiles contain extended periodicity associated with crystal structures, most of them do possess a degree of regularity in the fiber profile that imparts mechanical and optical advantage.

Figure 1.1: Schematic presentation of the cross-sections of solid core and hollow core PCFs. Grey region is high index material, white area is low index material.

1.1.2 Classifications of PCF

We may divide index-guiding PCFs into a number of subclasses, which are primarily determined by the geometrical dimensions of the fiber structures, as well as their specific properties. Four typical subclasses have emerged today as follows: large-mode-area (LMA) fibers possess relatively large solid core dimension and small air-filling fraction as shown in Fig. 1.2 (a), thus small refractive index contrast and weakly guiding will spread out the transverse optical field. High-numerical-aperture (HNA) fibers have a ring of relatively large air-holes as shown in Fig. 1.2 (b). Highly-

birefringent (HiBi) fibers induce a high geometrical birefringence by intentionally reducing the rotational symmetry (Fig. 1.2 (c)). Highly-nonlinear (HNL) fibers apply very small core dimensions to provide tight mode confinement as illustrated in Fig. 1.2 (d). All the fiber cross-sections shown in Fig. 1.2 are the commercialized PCF products from Crystal Fiber A/S [12]. Besides these commercialized structures, multi-core PCFs especially two-core PCFs are worth to be included as a subclass. They can be used as directional couplers, switches and even sensors.

Figure 1.2: (a) LMA-PCF. (b) HNA-PCF. (c) HiBi-PCF. (d) HNL-PCF.

The PBGF may be separated into sub-classes according to the structures as follows: hollow-core fibers, low-index-core fibers and Bragg fibers. Hollow-core fiber, as the

name indicates, allows majority of the optical power to propagate in the central hole of the fiber as shown in Fig 1.1 (b). Low-index-core fibers are formed by special designs of the core structures, such as the honeycomb of Fig 1.3 (a), and the modified honeycomb in Fig 1.3 (b). However, the propagating light concentrates in the high index portion of the core [13]. And more recently, some heterostructure of the PBGF have been proposed and investigated by Yan *et al.* [14]-[15] Bragg fibers are rotationally symmetric ring structures, which are unique compared with the other PBGF structures with individual holes/voids distributed in the cladding [4] [16].

Figure 1.3: (a) Standard honeycomb PBGF. (b) Modified honeycomb PBGF.

The background material of most PCFs is fused pure silica. But the research is never limited to the fused silica, other materials such as tellurite glasses, chalcogenide glasses and other heavy metal oxide glasses [17] have also been utilized for microstructure designs. Typically, the special properties of high nonlinear refractive index and high rare-earth solubility make these glasses noteworthy candidates for highly nonlinear applications, novel devices for mid-infrared laser transmission, and

compact active fiber devices [18]-[19]. Soft glass based PCFs can be made by an extrusion method where the extruded glass is pushed directly from the die to create the preform. The softening temperatures for these materials are quite low. Two thermally-matched soft glasses can be used to form an all-solid PCF [20].

Polymer materials with even lower softening temperatures have also been used in recent years to fabricate microstructured fibers [21]-[22]. An even more direct fabrication technique, called drilling-and-drawing, has been used to fabricate polymer PCFs. Polymer optical fiber technology has advanced rapidly in recent years, with the expectation that it can be one solution for the critical last mile of the telecommunication networks. Polymer PCFs made from polymethyl methacrylate (PMMA), allow many advantages over the silica PCFs [23]-[26]. Firstly, the fabrication is much easier due to the more favorable balance between surface tension and viscosity at the drawing temperature. This reduces the chance of holes collapsing and guarantees the maintaining of the air-hole shape along the fiber direction. Secondly, the microstructure is not restricted to close packed triangular arrangement of circular holes, as in the case for stack-and-drawing fabrication process. Thirdly, more material modifications are possible, owing to the much lower processing temperature and the intrinsic tunability of polymers [27]. This offers the potential of fabricating fiber with functionality not otherwise obtainable. However, the much higher intrinsic material loss of PMMA restricts many applications of such fibers. Furthermore, the maximum exposure temperature is only 70°C which is the melting point for PMMA [28].

1.1.3 Applications of PCF

In the previous section, we have discussed the fundamental differences between index-guiding and bandgap-guiding PCFs. However, both types of PCFs show a strong structure dependence of their fiber properties. Therefore, the degree of freedom is increased dramatically in the design. The distinguished properties in these novel fibers make them great candidates in optical communication systems. In order to deploy PCFs as transmission media, low loss and long length PCFs are particularly required. The intrinsic loss including the Rayleigh scattering and infrared absorption is less than that of a typical conventional fiber because most PCFs are composed only of single material (such as fused silica). Early days of 1999, fabrication of PCF was limited to only few meters with a loss of 240dB/km [29]. After four years, the loss was rapidly reduced to 0.28dB/km and 10km length could be achieved, according to the report by NTT, Japan [30]. Middle of year 2005, the review of Hitachi Cable in Japan reported the lowest loss to the best of our knowledge, 0.205dB/km at 1550nm wavelength for index-guiding PCF [31].

We have classified index-guiding PCFs into four main sub-classes according to their structure perspectives as well as their corresponding unique applications. LMA-PCFs provide new functionality to the field of fiber technology by allowing single-mode operation for a large wavelength range, even covering visible part of the optical spectrum [32]. Meanwhile a large spot size makes the fiber to fiber coupling simpler. Polarization effects are typically less important for this kind of highly-symmetric structure [33]. Single material in PCF means dopant is not necessarily required to achieve the guiding. The nonlinearity can be suppressed by the un-doped core as well

as the large core area [34]. The minimization of undesired nonlinear effects is crucial for many applications. The development of such LMA-PCFs is important for a wide range of practical applications, most notably those where high optical power delivery is required and wide single mode operation range is essential.

The extremely large index contrast between core and cladding is the main feature of HNA-PCF. The highest NA achieved is up to 0.9 [35] while for a typical step index fiber, the value is smaller than 0.3. The large core diameter usually causes the fiber to be multimode. Such high NA guarantees the efficient collection/distribution of light at a broad angle at the input/output port. This technique may dramatically increase the efficiency and power level of fiber lasers and may be potentially useful in collecting radiation in fluorescence-monitoring applications. They can be applied in the field of high power delivery, sensing, lighting system, laser pigtail, cladding pumping and nonlinear microscopy, etc. The outer layer of the air-hole ring structure can be deployed into grating devices to isolate the inner parts of an optical fiber so that the devices will be insensitive to environmental or external refractive index variations [36].

One of the important applications of HiBi-PCF is as polarization-maintaining fiber (PMF). In standard fiber transmission systems, fiber imperfections accumulated in the fabrication will introduce random birefringence leading to the polarization mode dispersion (PMD) effects [37]-[38]. This problem can be overcome in PMF by deliberately introducing a large uniform birefringence throughout the fiber. Conventional panda or bow-tie fibers can achieve this goal with a birefringence in the order of 10^{-4} [34]. Various HiBi-PCFs were proposed and birefringence value up to

10^{-3} could be easily achieved in such fibers [39]-[45]. The fabrication for such fibers is flexible and the index contrast is high. Only slight modifications should be done on the preform stacking to obtain non-degenerate fiber modes. In order to eliminate both the PMD and polarization modes coupling effects, single-polarization PCF has been achieved [46]. The large polarization dependent loss (PDL) in such novel design of absolutely single-polarization fiber indicates that the fiber guides only one polarization mode.

The possibility of fabricating very small core sizes (diameters down to $1\mu\text{m}$) enables us to create fibers with extremely small effective areas and high nonlinearity [17] [34]. The nonlinear coefficient is enhanced by large air-filling fractions. The HNL-PCFs are made with the purpose of tight mode confinement [47]. Furthermore, the dispersion profiles are designed to facilitate different nonlinear effects for special applications [48]-[49]. This makes our fibers ideal for applications like four-wave mixing [50]-[51], Raman amplification [52]-[53], etc. In the nonlinearity related research domain, most efforts are devoted into supercontinuum generation. Formation of broad continuous spectra along propagation of high power femto- or picosecond pulses through nonlinear media was firstly observed in 1970 [54] and has since then been studied extensively in various nonlinear materials [55]-[56]. Results in HNL-PCFs have previously been presented with pumping at the zero dispersion wavelength in both the visible [57] and the infrared wavelength range [58]. The HNL-PCF is an ideal medium for supercontinuum generation as the dispersion can be tailored to facilitate a specific operational region. So it is possible to convert light to both longer and shorter wavelength, resulting in an ultrawide spectrum covering more than an

octave. Such ultrawide spectrum can be applied for metrology, optical coherence tomography or spectroscopy and broadband light sources.

In PBGFs, PBG effect is used to confine light and the light is guided in the central core region. The transmission loss value is greatly improved in recent several years with the maturation of fabrication techniques. In 2003, Corning reported the loss value to be 13dB/km at 1550nm wavelength [59]. And in the next year, research groups in UK reported a value as small as 1.7dB/km [60]. Early year 2005, same group reported the lowest attenuation for hollow core PBGF, which is 1.2dB/km [61]. A typical hollow core PBGF structure could potentially lead to dramatically lower loss than the best conventional fibers of present. For this reason, the air-guiding PBGF was originally proposed for ultra low loss transmission in optical communication. Although it is still far away to deploy such novel fibers into long haul transmission system, it has already shown the great advantages in many subsystems. It provides the basis for high power delivery with negligible nonlinear effects and material damage. The nonlinear threshold power is very high, and the dispersion values can be scaled to extreme values [62], which will be useful for pulse compression and dispersion compensation. Furthermore, there is no Fresnel reflection at the open fiber end. Some other research areas such as atom guiding [10] and sensing [63] have been attractive in recent years as well.

Although no dopant is required to form the guidance in PCFs, we can still dope the solid cores with rare-earth material to achieve different applications [64]-[66]. PCFs doped with Erbium or Ytterbium have been studied and investigated in the past few years. These actively doped PCFs can be applied into fiber devices to improve the

performances. In particular, they can be designed with very small or very large mode areas to realize new fiber lasers.

The unique stack-and-drawing fabrication technique starts from the stacking of capillaries. Multiple cores can be easily introduced in such fibers, compared with the process in conventional multi-core fibers. The complex interactions between the modes in each core of a triple-core PCF are investigated by Roberts *et al.* [67]. Numbers of structures were proposed for polarization beam splitters [68] and some designs were utilized for sensing applications [69]-[70]. Among these research ideas, two-core PCFs have attracted most attention. An all-fiber curvature sensor has been proposed based on such two-core structure [69]. Coupling effects have been modeled and discussed, especially the dependence on air-filling fractions as well as wavelength. Similar analysis has been extended from silica fiber to polymer fiber, from index-guiding to bandgap-guiding. [26] [71]-[73]

Because of the air-holes in the microstructure, PCFs can be used as gas/liquid sensors. There have been explorations and discussions about PCFs in sensing applications for many years [74]. They have the following advantages compared with conventional fibers: large interaction field in the air-hole region, long interaction length along fibers and small volume gas/liquid requirement. We can also fill up those air-holes with different materials, polymer for example. Based on such hybrid material PCFs, we can induce grating structures inside. A great tunability of resonance wavelength and amplitude is obtained due to the strong temperature dependence of the polymer refractive index so that such structures can be used as temperature sensors [25].

Furthermore, due to the single material of PCF, a much lower and more uniform thermal expansion coefficient can be expected in such structure. An improved temperature stability compared with conventional fiber is achievable using this novel fiber. Temperature insensitivity has been demonstrated and observed in many PCF based devices, such as a long period grating (LPG) [75]. The temperature stability was dramatically improved in a HiBi-PCF based fiber loop mirror [76]. A thermally stable fiber Bragg grating (FBG) sensor formed with a Sagnac loop filter also included a section of pure silica HiBi-PCF [77]. Taking advantage of the high birefringence and the low temperature sensitivity of a piece of HiBi-PCF, a multi-wavelength fiber laser (MWFL) with a relatively short-cavity length and good temperature stability has also been demonstrated [78].

1.2 Objectives

As a new type of optical waveguides, PCF yields some significant advantages over conventional fiber in the areas of polarization, dispersion and nonlinearity. Optical devices based on PCFs are expected to possess some unique properties, such as tunable coupling between multiple cores, anomalous coupling characteristics between core and cladding modes. Intensive research interest has been attracted in the domain of PCF for almost ten years. A great effort has been contributed to fabrication of low-loss PCFs. Currently, numerous new ideas for such novel fibers are under investigations in more and more research groups and companies worldwide. An expectation exists among these groups that there are still lots of research field worth to be explored and investigated further. It is very exciting and challenging to contribute to this new research world in terms of designing new fiber components for

different applications. Therefore, the main objective of this thesis is to design novel PCF based devices for optical communication system, including HiBi-PCF, dispersion-compensating (DC) PCF, two-core PCF and PCF based LPG. The focus is to investigate the possibilities of birefringence tailoring, dispersion tailoring and coupling coefficient tailoring. Besides the systematic modeling and theoretical analysis, some experiments are worth to be carried out. For example, it is meaningful to take advantage of the temperature stability of a single-material PCF and deploy it into systems. The measurement of coupling coefficients is also crucial to verify the theoretical modeling results. PCF based LPG is investigated in detail both theoretically and experimentally, including their fabrication, transmission characteristics, and applications.

1. 3 Outline of Thesis

After the introduction of history and applications in Chapter 1, Chapter 2 presents the fundamentals of waveguide problems, and several theoretical models are discussed and compared. Due to the design flexibility of the air-hole size and arrangement in PCFs, the air-filling fraction can be very large, thus the approximation of weakly-guiding is no longer satisfied in many cases. For this reason, only vector-form Maxwell's wave equations can be used to solve the eigenvalues of the two dimensional waveguide cross-sections. By considering the numerical accuracy and computational efficiency, vector-form plane wave method and beam propagation method are chosen for the numerical modeling stated in this thesis.

In Chapter 3, HiBi-PCF designs are proposed and characterized. Both index-guiding and bandgap-guiding PCF structures with periodic elliptical lattices are designed and analyzed. The evolutions of birefringence values with the structure parameters are theoretically verified, such as the ellipticity, refractive index contrast, number of lattice layers, etc. Besides the theoretical studies, we also apply a type of thermally stable HiBi-PCF into an erbium doped fiber laser (EDFL) system to reduce the loop length as well as to improve the temperature stability.

We demonstrate in Chapter 4 the tailoring of dispersion values in standard and interstitial-hole assistant PCFs. The structure and wavelength dependence of chromatic dispersion is systematically analyzed. Dispersion characteristics are explored in various perspectives, such as ultra-high dispersion, ultra-flattened dispersion. A novel structure of DC-PCF is proposed based on concentric-core designs. The coupling between the two concentric cores occurs at 1550nm wavelength to obtain a large negative dispersion value. Such large dispersion can be utilized to effectively compensate the accumulated positive dispersion in a transmission system. This novel idea is further extended to a HiBi-PCF structure so that we can achieve effective dispersion compensation for a polarization maintaining system.

Chapter 5 shows the intensive theoretical and experimental investigation about the coupling effects in two-core PCFs. The derivations and constraints of coupled mode theory and super mode theory are both discussed in detail. Trials on fabrication of silica and polymer two-core PCFs are presented. Moreover, the coupling coefficient and the coupling coefficient dispersion are measured from the output interference spectrum. Various properties of these two-core structures, such as the structure

dependence and the wavelength dependence of the coupling coefficients are explored in this chapter.

In Chapter 6, we demonstrate the temperature insensitivity of PCF based LPGs. Point by point stress relaxation method using CO₂ laser and periodic photoelastic microbending technique are used to fabricate PCF based LPGs. The PCF based LPGs are compared with single mode fiber (SMF) based LPGs using theoretical calculation and experimental investigation. We investigate several applications of such grating device, such as grating pair based Mach-Zehnder interferometer, interferometer based on a LPG with assistance of a misalignment splicing point, and the measurement of torsion sensitivity using a LPG.

Chapter 7 summarizes the main achievements and draws the conclusions of this thesis. Discussions and recommendations of future work are presented.

The original contributions of this thesis are as follows:

- ◆ Design of a bandgap-guiding HiBi-PCF based on solid elliptical rods in the periodic cladding. Systematic analysis of the dependence for birefringent characteristics on lattice size, symmetry and index contrast. (Chapter 3)
- ◆ Deployment of a single material HiBi-PCF into a fiber laser system to effectively improve the temperature stability as a birefringent component. The thermal stability is found to have a ten-fold improvement compared with using conventional HiBi fiber. (Chapter 3)

- ◆ Design of an interstitial-hole assistant PCF structure and analysis of the modal properties. Design of a concentric-core DC-PCF achieving dispersion values as large as -6000ps/km-nm at 1550nm wavelength. Design of a DC-PCF with high birefringence for polarization maintaining system. (Chapter 4)
- ◆ Design and fabrication of two types of two-core PCFs with strong and weak coupling effects respectively. Proposal and derivation of a novel effective-index based coupled mode theory. Theoretical investigation of the strain insensitivity and structure dependence of the coupling. Measurements the coupling coefficient as well as its wavelength dependence from the interference spectrum, which match well with the theoretical calculations. (Chapter 5)
- ◆ Demonstration of the temperature insensitivity of PCF based LPGs using both CO_2 laser and photoelastic effects. Detailed comparison of PCF based LPGs with SMF based LPGs. Proposal of a grating based Mach-Zehnder interferometer with a misalignment splicing point. And the measurement of torsion sensitivity using PCF based LPG. (Chapter 6)

2

Fundamental Theory and Numerical Methods

2.1 Fundamental Theories

2.1.1 Maxwell's Equations

The well-known Maxwell's equations can be written in the following macroscopic form:

$$\nabla \cdot \mathbf{B} = 0 \quad (2.1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.2)$$

$$\nabla \cdot \mathbf{D} = \rho \quad (2.3)$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \quad (2.4)$$

where $\mathbf{E}$ is the electric field and $\mathbf{H}$ is the magnetic field. $\mathbf{D}$ is the displacement and $\mathbf{B}$ is the magnetic flux density. ρ is the density of electric charge and $\mathbf{J}$ is the current density (these two densities are zero for source-free waveguides). Two constitutive equations can describe the linear medium by $\mathbf{D} = \epsilon \mathbf{E}$, and $\mathbf{B} = \mu \mathbf{H}$, where $\epsilon = \epsilon_r \epsilon_0$ and $\mu = \mu_r \mu_0$, ϵ_0 and μ_0 are electric permittivity and magnetic

permeability of vacuum. ϵ_r and μ_r are relative electric permittivity and magnetic permeability of the specific medium, respectively. However, we usually assume all materials used here are impermeable, i.e. $\mu_r = 1$.

2.1.2 Wave Equations for Weakly-Guiding Fiber

For a time-invariant case, the electric field and magnetic field can be expressed in the form of a time harmonic:

$$\mathbf{E}(r, t) = \mathbf{E}(r) e^{j\omega t} \quad (2.5a)$$

$$\mathbf{H}(r, t) = \mathbf{H}(r) e^{j\omega t} \quad (2.5b)$$

Substituting them into Eqs. (2.2) and (2.4) and taking the curl on both sides, we can get:

$$\nabla \times (\nabla \times \mathbf{E}) = k_0^2 \epsilon_r \mathbf{E} \quad (2.6a)$$

$$\nabla \times (\nabla \times \mathbf{H}) = k_0^2 \epsilon_r \mathbf{H} \quad (2.6b)$$

where $k_0 = \frac{\omega}{c}$ is the free space wave number. Using the vector identity

$\nabla \times (\nabla \times) = \nabla(\nabla \cdot) - \nabla^2$, Eq. (2.6) can be derived and simplified to the form of:

$$-\nabla^2 \mathbf{E} - \nabla \left(\frac{\nabla \epsilon_r}{\epsilon_r} \cdot \mathbf{E} \right) = k_0^2 \epsilon_r \mathbf{E} \quad (2.7a)$$

Similarly, we can get the wave equation for the magnetic field:

$$-\nabla^2 \mathbf{H} - \frac{\nabla \epsilon_r}{\epsilon_r} \times (\nabla \times \mathbf{H}) = k_0^2 \epsilon_r \mathbf{H} \quad (2.7b)$$

In a conventional SMF, the weakly-guiding assumption is always satisfied because the refractive index contrast between the core and cladding is less than one percent.

Thus the spatial derivatives $\frac{\nabla \epsilon_r}{\epsilon_r}$ can be approximated to be zero. Effective index n_{eff}

can be interpreted as the ratio of the wavelength in the vacuum to the wavelength in the medium, or as the ratio of a phase rotation in the medium to the phase rotation in a vacuum. A pair of Helmholtz equations is obtained:

$$\nabla_t^2 \mathbf{E} + k_0^2 (\epsilon_r - n_{eff}^2) \mathbf{E} = 0 \quad (2.8a)$$

$$\nabla_t^2 \mathbf{H} + k_0^2 (\epsilon_r - n_{eff}^2) \mathbf{H} = 0 \quad (2.8b)$$

2.1.3 Wave Equations for PCF

The weakly-guiding assumption in conventional SMFs actually simplifies the wave equation (2.6) in to scalar form Helmholtz equations. In PCFs, due to the existence of the air-holes, the weakly-guiding assumption may not be satisfied when the air-filling fraction exceeds a certain value. Thus the full vector wave equations (2.6) and (2.7) rather than the scalar Helmholtz equations should be used to solve the EM problem. In a PCF waveguide (we assume that the waveguide is invariant in z-direction), a forward-propagating mode can be represented as

$$\mathbf{E}(x, y, z) = \mathbf{E}(x, y)e^{-j\beta z} \quad (2.9a)$$

$$\mathbf{H}(x, y, z) = \mathbf{H}(x, y)e^{-j\beta z} \quad (2.9b)$$

where $\beta = k_0 n_{eff}$ is the propagation constant. There are no strictly-bounded modes in a PCF, and the effective indices of these leaky modes are complex numbers. The imaginary part implies the radiation loss or confinement loss according to

$$Loss (dB / m) = \frac{20 \times 10^6}{\ln 10} \frac{2\pi}{\lambda(um)} \text{Im}(n_{eff}) \quad (2.10)$$

Substituting Eqs. (2.9a) and (2.9b) into (2.7a) and (2.7b), we can get another two sets of vector-form wave equations for solving the mode problem in PCFs:

$$(\nabla_t^2 + k^2 - \beta^2) \mathbf{E}_t = -\nabla_t (\mathbf{E}_t \cdot \nabla_t \ln \varepsilon_r) \quad (2.11a)$$

$$(\nabla_t^2 + k^2 - \beta^2) \mathbf{H}_t = (\nabla_t \times \mathbf{H}_t) \times \nabla \ln \varepsilon_r \quad (2.11b)$$

2.2 Numerical Methods

2.2.1 Overview

For the modeling of different complex microstructures in various PCF designs, proper choice of the numerical methods becomes essential. There have been a number of systematic numerical methods applied and analyzed in the past few years for theoretical studies of modes in various PCF structures, such as effective index method [32] [79] [80], finite element method [81]-[83], finite difference method [84]-[85], multi-pole method [86]-[87], boundary element method [88]-[89], Fourier decomposition method [90], plane wave method [91], beam propagation method [92]-[93], etc.

Some of the above methods are fundamentally straightforward for the understanding of waveguide theory, whereas others are more general. The two extreme methods are the effective index method and finite element method in terms of computational

efficiency. Effective index method is the first method developed to get the characteristic parameters of PCFs. It approximates the PCF microstructure to a step-index fiber with a cladding index equal to the effective index in the holey cladding region so that the periodic cladding lattice can be replaced by a uniform material [32] [79]-[80]. Therefore, a virtual step-index fiber is formed by this scalar approximation. Then all the theories and equations for conventional step index fiber can be applied to PCF. The effective cladding mode is the fundamental mode propagating in the infinite photonic crystal (PC) cladding under the condition that the core is absent. Effective index method is simple and computationally efficient to qualitatively model PCFs. However, it is not very accurate for dispersion and bending analysis since it underestimates the existence of air-holes in the cladding. Moreover, polarization properties and structures based on bandgap mechanism can not be solved based on this method. Finite element method (FEM), as the name indicates, divides the waveguide into finite number of small elements. It is recognized as the most accurate and reliable numerical method. However, this method is highly-demanding on memory, thus computationally intensive especially compared with the effective index method. A complex definition for the domain and mesh are required for the calculation. Therefore, we did not adopt it for the general modeling of our PCF designs, and rather we use it as a reference for the results comparison. The perfect electric/magnetic conductor or simply zero boundary condition was used in traditional FEM for conventional step index fiber. But due to the fact that all modes in PCFs are leaky, so these boundary conditions will cause reflection at the boundary, which can give rise to significant errors. To overcome this problem, there have been amount of research work proposing the perfectly matched layer (PML) as the boundary condition for some FEM mode solvers [81]-[83].

Finite difference method can be formulated in both time domain and frequency domain. It may be used to describe arbitrary structures and even integrated optics, but this method is numerically intensive and requires detailed treatment of boundary conditions. Multi-pole method applies to a finite problem domain with an appropriate boundary condition, similar to any domain-methods such as finite element method and boundary element method. But it can only be applied to those structures with clear index change at boundaries. Furthermore, this method has the constraint of calculating the confinement loss only for structures with circular air-holes. Fourier decomposition method is fully vectorial and can calculate the confinement loss of leaky modes accurately for arbitrary PCF structures [94]. This method is based on a polar coordinate, but we have to adjust the boundary conditions separately for each calculation. Further more, for those super-structures, this method requires a large number of radial steps and azimuthal Fourier components in order to search for the even and odd mode pairs.

Among these methods, semi-vector beam propagation method (BPM) and plane wave method (PWM) are chosen to solve the wave-guiding problems within our research scope. BPM method is conceptually straightforward and efficient. It can automatically include the effects of both guided and radiating modes, mode coupling and mode conversion, polarization and nonlinearity effects. PWM is up to now one of the most-widely used methods for bandgap structure calculation due to its efficiency and applicability. It works in frequency domain, giving a fast interpretation of the photonic crystal (PC) properties.

2.2.2 Beam Propagation Method (BPM)

BPM is essentially a particular approach for approximating the exact wave equations for monochromatic waves, and solving the resulting equations numerically. The scalar field assumption allows the wave equation to be written in the form of the well-known Helmholtz equation for monochromatic waves. The approach is readily applied to complex geometries without having to develop specialized versions. It considers coupling between forward and backward propagation waves and can account for reflection phenomenon, including resonant effects as found in grating structures [95].

Figure 2.1: Illustration of grids in BPM algorithm: n is the number of planes in the z -direction, i is the number of grid points in x -direction.

The geometry of the microstructured waveguide problem is defined entirely by the refractive index distribution. The field in the transverse plane is represented only at discrete points on a grid, and at discrete planes along the propagation direction shown in Fig. 2.1, numerical equation is derived to relate the fields in the previous and next planes as follows:

$$\frac{u_i^{n+1} - u_i^n}{\Delta z} = \frac{i}{2k} \left(\frac{\delta^2}{\Delta x^2} + (k(x_i, z_{n+1/2})^2 - \bar{k}^2) \right) \frac{u_i^{n+1} + u_i^n}{2} \quad (2.12)$$

where $\delta^2 u_i = (u_{i+1} + u_{i-1} - 2u_i)$ and $z_{n+1/2} = z_n + \Delta z/2$, u_i^n denotes the field at the transverse grid i and longitudinal plane n , and assuming the grids and planes are equally separated by Δx and Δz . $k(x, z) = 2\pi n(x, z)/\lambda$ is the x-direction spatially dependent wave number, $\bar{k}$ is the average phase variation of the field which is a constant. This elementary propagation step is repeated to determine the field throughout the structure. A commonly used transparent boundary condition which allows the field at the boundary point related to the interior point, allowing the radiation to freely escape from the computational domain.

The modes in PCFs are usually leaky, thus dispersion characteristics of various structures are solved using a correlation method [95]. An incident field is launched into a geometry that is z-invariant, and some form of BPM propagation is performed. Since the structure is uniform along z direction, the propagation can be equivalently described in terms of the modes and propagation constants of the structure. The incident field can be expanded in the modes of the structures as:

$$\phi_{in}(x, y) = \sum_m c_m \phi_m(x, y) \quad (2.13)$$

The propagation through the structure can then be expressed as

$$\phi(x, y, z) = \sum_m c_m \phi_m(x, y) e^{-j\beta_m z} \quad (2.14)$$

where β_m is the propagation constant of the m th mode. During the propagation, a correlation function between the input field and the propagation field is obtained:

$$P(z) = \sum_m |c_m|^2 e^{-j\beta_m z} \quad (2.15)$$

From this expression, we get that a Fourier transform of the computed correlation function $\tilde{P}(X)$, which has a spectrum with peaks at the modal propagation constant β_m :

$$\tilde{P}(X) = \sqrt{2\pi} \sum_m |c_m|^2 \delta(X - \beta_m) \quad (2.16)$$

There are several reasons for us to choose BPM: 1) it is conceptually straightforward, allowing rapid implementation of the basic technique; 2) it is generally very efficient and the computational complexity can be even optimized by choosing appropriate number of grid points used, 3) it is readily applicable to complex geometries, so that it is suitable for modeling our special fiber designs, 4) it includes the effects of guided fields, radiating fields, and mode coupling, which is very suitable for analysis of confinement loss and the coupling effects in our two-core structures.

2.2.3 Plane Wave Method (PWM)

PWM is highly developed and is associated with the evolution of PCFs because of the periodic PC cladding [96]. This method was originally proposed for the band calculations in a periodic 2D structure, and the light propagating in the place of periodicity [91]. The PWM expansion method operates in reciprocal space. The transition from the real space to the reciprocal space is shown in Fig. 2.2. R_1 and R_2 are the primitive lattice vectors, G_1 and G_2 are the reciprocal lattice vectors. Λ is the lattice size in real space while $2\pi/\Lambda$ is the reciprocal lattice size. The optical modes properties of a PCF structure can be obtained from the dispersion relation $k = k(\omega)$.

It connects the propagation constant k with the frequency ω . In this expansion method, we find a different solution for every value of k . It is possible to determine the solution of the eigenvalue problem by only considering the k restricted to the first Brillouin zone. The first Brillouin zone is defined as the smallest possible region in reciprocal space that may be used to represent the full periodic structure.

Figure 2.2: (a) The real-space (b) The reciprocal space of a 2D periodic structure with a hexagonal symmetry. R_1 and R_2 are the primitive lattice vectors, Λ is the lattice size, G_1 and G_2 are the reciprocal lattice vectors, the grey-area is the first Brillouin zone, Γ , M and K are the symmetry points.

The $\mathbf{H}$ -field wave equation is chosen to solve in this expansion method because it can reduce the computational complexity. The alternative form of Eq. (2.6b) is expressed as:

$$\nabla \times \left[\frac{1}{\varepsilon(\mathbf{r})} \nabla \times \mathbf{H} \right] = k_0^2 \mathbf{H} \quad (2.17)$$

where $\varepsilon(\mathbf{r})$ is a position-dependent dielectric constant; $\mathbf{r}$ lies in the plane normal to the direction of propagation. Expanding the magnetic $\mathbf{H}$ -field and the dielectric function in a series of plane waves, we obtain:

$$\mathbf{H}(\mathbf{r}) = \sum_{\mathbf{G}} \sum_{j=1,2} H_{\mathbf{G},j} \hat{\mathbf{e}}_j e^{j(\mathbf{k}+\mathbf{G})\cdot\mathbf{r}} \quad (2.18a)$$

$$\varepsilon(\mathbf{r}) = \sum_{\mathbf{G}'} \varepsilon(\mathbf{G}') e^{j\mathbf{G}'\cdot\mathbf{r}} \quad (2.18b)$$

$\hat{\mathbf{e}}_j$ is the unit vector orthogonal to $(\mathbf{k}+\mathbf{G})$. $\mathbf{k}$ is the wave vector. $\mathbf{G}$ and $\mathbf{G}'$ are the reciprocal lattice vectors, which are used for the Fourier expansions of the field and dielectric functions, respectively. $H_{\mathbf{G},j}$ is the Fourier expansion coefficients for the field. The Fourier coefficient $\varepsilon(\mathbf{G}')$ is defined by

$$\varepsilon(\mathbf{G}') = \frac{1}{S} \int_S \varepsilon(\mathbf{r}) e^{-j\mathbf{G}'\cdot\mathbf{r}} d\mathbf{r} \quad (2.19)$$

where the integration is carried out over the area S of one unit cell of the lattice. Substituting Eqs. (2.18a) (2.18b) into Eq. (2.17), two standard eigenvalue-equations are obtained, corresponding to two independent polarizations: E -polarization mode and H -polarization mode.

$$\sum_{\mathbf{G}'} |\mathbf{k} + \mathbf{G}| |\mathbf{k} + \mathbf{G}'| \varepsilon^{-1}(\mathbf{G} - \mathbf{G}') H_{\mathbf{G}',1} = k_0^2 H_{\mathbf{G},1} \quad (2.20a)$$

$$\sum_{\mathbf{G}'} |\mathbf{k} + \mathbf{G}| |\mathbf{k} + \mathbf{G}'| \varepsilon^{-1}(\mathbf{G} - \mathbf{G}') H_{\mathbf{G}',2} = k_0^2 H_{\mathbf{G},2} \quad (2.20b)$$

$H_{\mathbf{G},j}$ is also the Fourier expansion coefficients. Besides using this equation to calculate the band diagram of 2D PC problems [97], we can also use it to deal with off-plane light propagation, such as calculating the modes in PCFs. Then the $\mathbf{E}$ -field can readily be obtained from:

$$\mathbf{E} = \frac{1}{j\omega\varepsilon} \nabla \times \mathbf{H} \quad (2.21)$$

Although we cannot use this method to handle loss problem since material is assumed to be lossless, PWM still has the advantages of a good balance between accuracy and efficiency.

2.3 Conclusions

In this chapter, the fundamental theories for PCF based problems have been investigated. The weakly-guiding approximation may not be satisfied in many cases of PCFs. Therefore vector-form wave equations for holey structures have been mathematically derived from the basic Maxwell's equations. Since these wave equations cannot be solved analytically, various numerical methods have been discussed and compared to calculate the modes in microstructured waveguides. Among them, beam propagation method (BPM) and plane wave expansion method (PWM) have been chosen to model and explore the properties of PCF designs. BPM is a proper choice by considering computational efficiency and accuracy, and it can handle loss problems. PWM is a unique method able to search the photonic bandgaps in periodic structures. Moreover, it can be specifically used to efficiently distinguish the mode degeneracy.

3 Highly-Birefringent PCF

3.1 Introduction

The microstructure of PCF opens a great freedom and flexibility. The numerical methods introduced in chapter 2 can be used to implement the modeling and theoretically verify the proposed new structures. As a potential candidate for the transmission medium, birefringence management in PCFs is an important and useful direction for novel fiber designs. In this chapter, we will propose HiBi-PCFs based on index-guiding and bandgap-guiding mechanisms. Temperature stability of HiBi-PCF is experimentally verified.

In standard fiber transmission systems, imperfections in the core-cladding interface introduce random birefringence that leads to randomly polarized light. This is often referred to as polarization mode dispersion (PMD) [38]. Problems with random birefringence are overcome by deliberately introducing a large uniform birefringence throughout the fiber. Highly birefringent SMF (HiBi-SMF), mostly utilized as polarization maintaining fiber (PMF), allows light propagating with preferred polarization direction. PMF is of great importance to optical communication networks.

Their polarization maintaining property can be used to deliver polarized light for a relatively long distance. Their high PMD can be used to compensate the PMD induced in long-haul optical networks [98]. Such fiber can also be employed for various polarization-sensitive applications, e.g. PMD measurement [99]. In PMFs, i.e. panda fiber and bow-tie fiber, high birefringence is achieved by introducing stress applying parts (SAPs) around core in the fiber. Therefore, core material is anisotropic as a result of the stress. This kind of birefringence can be regarded as stress-induced birefringence. In fact, birefringence can also be achieved by intentionally reducing the rotational symmetry of the fiber structure (especially the core structure). This type of birefringence is called geometrical birefringence. Geometrical birefringence is not employed for conventional PMF fabrication because the index difference between the doped core and pure-silica cladding is too small to achieve a high birefringence.

In a perfectly circular-symmetric structure, the propagation constants for two orthogonal polarization modes are equal, which is also applicable to PCFs. As the peculiar index profiles of PCFs have suggested, they offer great flexibility in introducing geometrical birefringence. By designing the air-hole distribution, a highly asymmetric core is achieved and a large effective index difference between two polarized modes can be obtained. Since the advent of air-silica PCFs, research on geometrical birefringence has thrived [42] [43] [100]-[103], partly due to the fact that symmetry of the core can be easily broken in such high index-contrast microstructured fibers. Birefringence of the order of 10^{-3} is demonstrated in such fibers. The birefringence of commercial PMFs are usually around $3 \sim 5 \times 10^{-4}$ [104]. So the birefringence achievable in PCFs is about one order of magnitude higher than that in conventional PMFs.

Most of the HiBi-PCFs introduced in the literature are of index-guiding type. Some research work also extend such design direction to bandgap PBF (PBGF) [105]. Later experiment attempt even demonstrated group birefringence as high as 2.5×10^{-2} around $1.55 \mu\text{m}$ wavelength in bandgap fiber [106]. However, such hollow-core HiBi fibers are not very compatible with existing optical fiber systems though they exhibit high birefringence. Especially, its splicing with conventional SMF remains problematic for normal applications. Moreover, distortion of cladding photonic crystal (PC) near core region is inevitable in fabrication of such hollow-core fibers, which is likely to make such fibers suffering from surface modes [105].

Designing the air-holes arrangement in PCFs can induce very large geometrical birefringence, rather than using doped materials as SAP to get stress-induced birefringence. So most HiBi-PCFs are typically made of only a single material (fused silica in most cases), thus lower and more uniform thermal expansion coefficient can be expected from this novel fiber. By taking advantage of the high birefringence and temperature insensitivity, HiBi-PCFs have been deployed into various subsystems to improve the thermal performance, such as interferometers [107] and fiber Bragg grating (FBG) based sensors [77]. We will apply such highly birefringent and thermally stable novel fiber into an erbium doped fiber laser (EDFL) system to reduce the loop length as well as to improve the temperature stability.

3.2 Design of HiBi-PCF

3.2.1 Design of Index-Guiding HiBi-PCF

In a standard PCF, the six-fold rotational symmetry guarantees the degeneracy of the fundamental modes. Most reported designs reduce the symmetry of the fiber core by changing the air-hole size near the core, thus it is named localized birefringent structures [42] [100]. In this section, we will propose a HiBi-PCF structure with two-fold rotational symmetry and theoretically investigate its characteristics. The birefringence is induced by identical elliptical air-holes in the overall cladding. As a result, the fiber decreases its rotational symmetry.

Figure 3.1: Schematic of a periodic microstructured EH-PCF, the defect in the center is denoted by the dashed circle.

A typical four-ring structure is shown in Fig. 3.1 and we call it elliptical-hole PCF (EH-PCF). The dashed circle region is the core of the microstructure. The refractive index of the central core region can be same as the background fused silica, or doped with different material. In this section, we use pure silica as background material and

the index is 1.45. The grey region is the air-hole and the refractive index is 1. The five parameters defining the structure are: the number of air-hole rings N , the diameters of the air-holes (d_x and d_y) in horizontal and vertical directions and lattice sizes in two different directions due to the “squashing” of a typical triangular array (Λ_a and Λ_b). Λ_a is fixed at $3\mu\text{m}$ through our calculation. Semi-vector BPM (SVBPM) module from the commercial *RSoft* package is used to calculate the effective mode indices of the two non-degenerate fundamental modes [95] (The typical artificial birefringence obtained by modeling a perfect symmetric structure is $\sim 1 \times 10^{-5}$). The parameters used in the SVBPM are as follows: the domain size is $26\mu\text{m} \times 20\mu\text{m}$, the numbers of grid points along two transverse directions are 260 and 200 (a convergence test is done accordingly for the effective mode index, which can be accurate up to the 5th significant figure after the decimal point as shown in Fig. 3.2 (c)), and the propagation step size in longitudinal direction is $0.1\mu\text{m}$. The transparent boundary condition is used to enable leaky mode analysis. The computational time for calculating one fundamental mode will be approximately one minute which is about two times longer than the scalar BPM (for Pentium 4 CPU 2.4GHz, 1.00GB of RAM).

Figure 3.2: Transverse electric field of (a) HE_{11}^x ; (b) HE_{11}^y modes at $\lambda=1550\text{nm}$; (c) convergence test, where $\Lambda_a=3\mu\text{m}$, $\Lambda_b=0.72\Lambda_a$, $d_x=1.125\mu\text{m}$, $d_y=0.6d_x$.

The field distribution for the non-degenerated HE_{11}^x and HE_{11}^y modes for $\lambda=1550\text{nm}$ is shown in Fig. 3.2 (a) & (b). The radiation loss is included and can be calculated according to Eq. (2.10). The modal indices (real part) for both x-polarized and y-polarized modes are shown in Fig. 3.3, and the inset shows the imaginary effective index which implies the loss. The effective index for the x-polarized mode is larger than the y-polarized mode. This is mainly due to the larger mode field diameter along the x-polarization direction. The confinement loss as small as 0.8dB/m is achieved at 1550nm wavelength. This can be further improved by adding more layers of air-holes [108]: it will be reduced to 0.09dB/m and 0.02dB/m when we have five and six rings of air holes respectively. It is noted that the confinement along x-polarization is better than y-polarized mode. This is because the effective width of cladding is larger in the x-polarized direction, which shows a stronger confinement.

Figure 3.3: Calculated effective indices with varying wavelength for HE_{11}^x and HE_{11}^y modes. The inset is the imaginary part of the effective indices.

Upon achieving the effective indices of HE_{11}^x and HE_{11}^y modes, the birefringence can be calculated for a range of wavelength by:

$$B = n_{eff}^x - n_{eff}^y \quad (3.1)$$

where n_{eff}^x and n_{eff}^y are the effective indices of HE_{11}^x and HE_{11}^y modes respectively.

By varying the ellipticity of the air-holes or the ratio between the lattice sizes in two different directions, we can achieve different birefringence values as shown in Fig. 3.4.

The effect of lattice difference between Λ_a and Λ_b due to the elliptical transformation is found to be less significant compared with the ellipticity of the air-holes from the two figures. The global birefringence of the microstructure can reach up to 10^{-3} at 1550nm when we decrease the ratio of hole-diameter in vertical and horizontal directions (d_y/d_x). The B value is nearly three times higher than conventional panda PMF.

Figure 3.4: Calculated birefringence versus wavelength for EH-PCF with (a) different elliptical air-holes, (b) different lattice ratio.

The ellipticity is varied in our birefringence calculation, while the air-filling fraction for the elliptical structure is kept constant $A_{\text{elliptical}} = \pi d_x d_y = \pi 0.25 \Lambda^2$. Birefringence value as large as 1×10^{-3} is obtained as shown in Fig. 3.4. We can also dope the center region with high index material. For example, if the refractive index of the central defect is 1.462, the birefringence is calculated and the results are shown in Fig. 3.5. The curve exhibits the same behavior when the number of air-hole rings N is less than five, thus birefringence value is determined by the inner most two rings. We can expect the same behavior when N increases because outer rings of air-hole have less significant effects on the mode. But the calculated birefringence is decreased with doping especially when the ellipticity is increased. It is because the long axis of the central doped region is along the short axis y of the fiber as shown in Fig. 3.1. Thus the birefringent core effect will suppress the asymmetry birefringent effects of the holey cladding.

Figure 3.5: Birefringence value of EH-PCFs with different ellipticity. r is the ratio of air-hole diameter in the short axis to the long axis.

3.2.2 Design of Bandgap-Guiding HiBi-PCF

A novel bandgap-guiding HiBi-PCF (HiBi-PBGF) is proposed in this section. The high-index rods in the cladding are elliptical shape and isolated in another solid material of low-index. The contributions of elliptical rods, lattice ratio as well as the index contrast to the birefringence are evaluated theoretically. Although there might be difficulties searching for the two solid materials for fabrication. There are a lot of advantages for such all solid structure. Perturbation of cladding PC does not exist in such fiber. Hence surface mode problem is eliminated. The solid core promotes integration with current optical fiber communication devices. Moreover, the PBG guidance will allow us to miniaturize the device size owing to the fact the fiber is tolerant to small bending radius. Comparing to air-core bandgap fiber, all-solid bandgap fiber is better to realize rare-earth doped amplifier and laser or to write Bragg gratings which are widely used in photonics. Furthermore these fibers should be easier to fabricate and splice for its elimination of mechanically unstable holey structure.

(a)

Figure 3.6: (a) Photonic bandgap fiber with elliptical high-index rod immersed in low-index background material. (b) Gap map of the PC cladding.

The cross-section of our proposed all-solid HiBi-PBGF is shown in Fig. 3.6 (a). It is made of high-index rods (n_2) immersed in low-index background material (n_1). Λ_a , Λ_b , d_x and d_y are the four parameters to define the lattice arrangement and the shape of the rods. Two thermally matched soft glasses can be used for fabricating such fibers. Similar non-birefringent PBGF has recently been reported in [109]. Refractive indices for the high-index SF6 and low-index LLF1 glasses are 1.79 and 1.54, respectively. The structure is derived from an equilaterally triangular-latticed PC by compressing it in y direction, so that the aspect ratio of a single ellipse is $d_y/d_x=0.6$ and the lattice ratio is $\Lambda_b/\Lambda_a=0.72$. The parameters for the fiber are chosen as $\Lambda_a=3\mu\text{m}$, $\Lambda_b=2.16\mu\text{m}$, $d_x=1.125\mu\text{m}$, $d_y=0.675\mu\text{m}$. The structural compression can be done during fiber drawing, following a technique deployed in [110]. As a result, the fiber decreases its rotational symmetry from six-fold to two-fold. The PC cladding given in Fig. 3.6 (a)

exhibits forbidden gaps in the periodic transversal plane when a large propagation constant is assumed in the out-of-plane direction. Such photonic bandgaps are shown in Fig. 3.6 (b), which is calculated using PWM. The calculation of the illustrated bandgap map takes around 10-20 minutes depending on the speed of the system. The wavelength is normalized to the pitch value Λ_a . Notice that the diagram is applicable to PBGFs whose proportion is the same as that shown in Fig. 3.6 (a), but with different scaling factors Λ_a and Λ_b [111][112]. The largest shaded region is the primary gap region, which will be used for achieving PBG guidance. It is noticed that the core line ($n_{eff}=1.54$) crosses the primary gap region from $\sim 0.4\Lambda_a$ to $\sim 0.6\Lambda_a$. For Λ_a value at $3\mu\text{m}$, we would expect PBG guidance from wavelength $\sim 1.2\mu\text{m}$ to $\sim 1.8\mu\text{m}$.

Due to the effect of PBG, light of certain frequency is not allowed to escape from the core. As a consequence, the light transmission in PBGF is wavelength dependent. The n_{eff} values of fundamental HE_{11}^x and HE_{11}^y modes at $\lambda=1550\text{nm}$ are calculated to be 1.5178 and 1.5169 respectively. Subsequently, by varying the wavelength, we obtain dispersion curves (Fig. 3.7) and the loss spectrum (Fig. 3.7, inset at up-right corner) for both modes. It can be observed that these effective indices are less than the refractive indices of both the cladding rods and the background glass. This confirms the bandgap-guiding nature of the waveguide from $1.2\mu\text{m}$ to $1.8\mu\text{m}$.

Figure 3.7: Calculated effective indices with varying λ for HE_{11}^x and HE_{11}^y modes. The inset is the confinement loss for two polarization modes and mode field pattern.

The confinement loss is calculated to be very high, which is 612dB/m and 978dB/m for HE_{11}^x and HE_{11}^y respectively at $\lambda=1550\text{nm}$. The high confinement loss is due to small number of cladding rings. This loss can be easily reduced by adding more layers of rods in the cladding [113]. The radiation loss for the HE_{11}^x at 1550nm will be reduced to 93dB/m and 19dB/m when solid-rod rings in the cladding are five and six respectively. The relationship of the confinement loss versus the number of rings is shown in the inset of Fig 3.7 for both x-polarized and y-polarized modes. A larger-sized core will also help to improve the confinement. From the inset of Fig. 3.7, we observe that the loss is the lowest in the range from $1.4\mu\text{m}$ to $1.6\mu\text{m}$, which is in agreement with the gapmap shown in Fig. 3.6 (b). If the operating wavelength goes outside the bandgap, the mode will not be effectively confined in the core. It is

interesting to notice that the x-polarized fundamental mode experiences smaller radiation loss than the y-polarized counterpart. The polarization dependent loss (PDL) implies the radiation efficiency is smaller in x-direction which might be due to the effective width of the cladding region along x-direction is larger than that along y-direction.

Figure 3.8: Calculated birefringence versus wavelength for solid rods with different ellipticity.

Numerical calculations have shown that the birefringence in the proposed PBG fiber can be easily achieved in the order of 10^{-3} . The birefringence value in our calculations is conducted for the whole region of the bandgap and it does not exhibit monotonic variation with wavelength. As shown by the curve with open squares in Fig. 3.8, the birefringence experiences a decrease with the increase of wavelength. This aspect is different from previously reported HiBi-PBGFs [114]. The overall birefringence is attributed to two factors: the birefringent cladding and the core shape. Due to the elliptical rods, the cladding can be approximated by an anisotropic homogeneous

medium. High birefringence at bandgap edges thus can be explained by the large portion of mode distribution into the birefringent cladding. The minimum B value occurs at the middle of the PBG, as the core mode there is well-confined and the contribution of cladding is minimized. In order to better understand the significance of different contributions to the birefringence, we calculate birefringence as cladding rod's ellipticity d_y/d_x and the lattice ratio Λ_b/Λ_a are varied. The evolutions of the birefringence are shown in Fig. 3.8 when we change the ellipticity of the solid rods. The minimum birefringence is increased from 0.75×10^{-3} to 1×10^{-3} when the d_y/d_x ratio varies from 0.7 to 0.5. Since the lattice ratio is fixed at $\Lambda_b/\Lambda_a=0.72$, so the core shape is not changed significantly. Consequently the increment of the birefringence is relatively small. PBG-guiding range shifts to a longer wavelength by $\sim 200\text{nm}$ due to change in cladding bandgap.

The symmetry of the core, which can be reflected by the cladding lattice ratio Λ_b/Λ_a , is another tunable parameter for birefringence. The Λ_b/Λ_a ratio is varied from 0.72 to 1.0 by fixing the ellipticity at $d_y/d_x=0.6$, $\Lambda_a=3\mu\text{m}$, and the result is shown in Fig. 3.9. We notice that the birefringence is decreased by half at $1.55\mu\text{m}$ when we change our structure in Fig. 3.6 to an equilaterally triangular-latticed structure. However, the PBG operation region is not shifted much. This is because the bandgap is mostly determined by the shape and index of the high index rods. Therefore, other than the contribution of structure asymmetry to the high birefringence, the index contrast in our proposed structure is also expected to have an important impact. Fig. 3.10 illustrates the decrease of birefringence when varying the index of the high index rods. The birefringence is decreased by one order if the index of solid rods is decreased from 1.79 to 1.65. Furthermore, the transmission window is red-shifted with the

increase of index contrast by more than 400nm. The evaluations of the impacts of the above factors to high birefringence indicate that our HiBi-PBGF can be tailored flexibly.

Figure 3.9: Calculated birefringence versus wavelength for different lattice ratio.

Figure 3.10: Calculated birefringence with different high-index rods.

For the designs in these two sections, their birefringence values are all scalable with the lattice period. So it is convenient to obtain the structures with similar mode field diameter as in the standard SMF, which promotes an easy splicing. The idea of elliptical inclusions in the microstructure cladding gives the global birefringence, which makes stacking and drawing fabrication easier since we only require uniformly latticed preforms. Moreover, the solid core PBGF design enables the better splicing with current optical fiber devices compared with hollow-core PBGFs.

3.3 Application of HiBi-PCF

In this section, an improved temperature-stable multi-wavelength EDFL source using a HiBi-PCF based Sagnac loop filter is developed. A relatively short length of HiBi-PCF as a birefringent component is spliced together with a section of EDF and a 3dB coupler to form the Sagnac loop filter. Taking advantage of the high birefringence and the low temperature sensitivity of the HiBi-PCF, a multi-wavelength fiber laser (MWFL) with a relatively short-cavity length and good temperature stability is demonstrated.

3.3.1 Introduction of MWFL

Wavelength division multiplexing (WDM) is an attractive technology that enables the transmission of multiple wavelength channels in a single optical fiber. With the massive expansion of WDM technology, EDFLs simultaneously emitting in multiple wavelengths over the 1550nm wavelength range have been extensively studied in recent years [115]-[120]. The basic requirements for this multi-wavelength optical source include a large number of lasing lines over a broad wavelength span, high

optical signal-to-noise ratio (OSNR) and moderate output power. Several techniques have been proposed to achieve MWFL with fixed wavelength spacing using cascaded linear cavities [115], polarization hole-burning effect [116], and a fiber grating based Sagnac loop filter with liquid nitrogen for room temperature operation [117], a Mach-Zehnder comb filter [118], an in-fiber comb filter [119], and a fiber Fabry-Perot filter [120] in a single-fiber cavity. However, the use of a fiber Fabry-Perot filter increases the insertion loss of the cavity and a Mach-Zehnder filter is sensitive to environmental perturbation, such as temperature change or vibration. Besides, in our recent work [121], we have proposed a multi-wavelength source by using a polarization-maintaining erbium-doped fiber (PM-EDF) as a gain medium. Good performance at room temperature has been achieved. However, there are two main problems in using the PM-EDF in this fiber laser system. Firstly, to employ both high birefringence and high erbium-doped concentration will suppress the effects of each other [121]. Thus the concentration of erbium ions of the PM-EDF is relatively low, which results in a small output optical power of the fiber laser. Moreover, because of the large thermal coefficient of the SAP in the PM-EDF, this laser source is expected to be very sensitive to the environmental temperature variation. The second problem commonly exists in most of the above techniques. Thus, for an EDFL that can work in a harsh environment, the temperature-induced instability must be overcome.

3.3.2 Experimental Setup and Operating Principle

The first experimental setup of the proposed MWFL is shown in Fig. 3.11. The structure of the EDFL is formed by a Sagnac loop filter and a reflector, and consists of a 1480/1550nm WDM coupler, a section of PM-EDF, a polarization controller, a 3dB

fiber coupler, and a linearly chirped FBG as a fiber mirror (a 17.5nm stop band of over 25dB centered at 1545nm). It consists of a single gain medium using 15m elliptical-core PM-EDF with a numerical aperture of 0.26, a birefringence of 2.40×10^{-4} at 1550nm and an erbium ion concentration of $3 \times 10^{24} \text{m}^{-3}$. The pump laser is a stable laser diode with a power of 180mW at 1480nm. This power level is fixed throughout our experiment.

Figure 3.11: Schematic diagram of first setup of the proposed MWFL.

The high birefringence produces a wavelength-dependent phase difference δ between the components of the fast and slow axes of the light propagating in the loop, that is,

$$\delta = 2\pi BL / \lambda \quad (3.2)$$

where B is the birefringence, L is the length of the HiBi fiber and λ is the operation wavelength. The phase difference of counter-propagating light exiting the loop filter at the 3dB coupler is wavelength dependent. The intensity transfer function of the fiber loop is periodic, and is given as

$$T(\lambda) = \sin^2(\delta / 2) \quad (3.3)$$

The resonance wavelength of the loop filter depends on the birefringence and length of the HiBi fiber, and is given by

$$\lambda = 2BL / (2k + 1) \quad (3.4)$$

where k is an integer determined by the ratio of total gain and loss of the laser cavity.

The wavelength separation between two transmission peaks of the Sagnac loop filter's output is given by

$$\Delta\lambda = \lambda^2 / BL \quad (3.5)$$

Thus, the channel spacing of the EDFL is determined by the birefringent component only, which is the HiBi fiber within the Sagnac loop filter.

3.3.3 Results and Discussion

In order to investigate the temperature stability of the EDFL in Fig. 3.11, we control the temperature of the PM-EDF with a thermal-heater from room temperature to 100°C. The average resonance variation is obtained from a repetition test over 10 hours and the spectral data are recorded every 10 minutes. Thus the results can concisely indicate the temperature stability improvement. The temperature sensitivity of the lasing wavelength is 46pm/°C, and the temperature sensitivity of the channel spacing is 0.5pm/°C.

Figure 3.12: Schematic diagram of second setup of the proposed MWFL.

Figure 3.13: Transmission spectra as a function of temperature for the panda PMF based MWFL.

In the EDFL system, the instability is mainly caused by the homogeneous gain broadening of EDF and the temperature insensitivity of the birefringent component. However, in case of the single gain medium, it is difficult to distinguish the influences of the homogeneous gain broadening of EDF and SAP thermal effects on the laser

instability. So we replaced the PM-EDF with 10m EDF spliced with a section of 4.8m panda PMF as shown in Fig. 3.12. Here, our effort is to improve the laser system's temperature stability by improving the birefringent component, so only the section of PMF is applied on the thermal heater for temperature change. The EDF has a numerical aperture of 0.24, and an erbium ion concentration of 1500ppm, and the panda PMF has a birefringence of 3.875×10^{-4} at 1550nm. When we increase the temperature from 30°C to 90°C, the corresponding spectra for this fiber loop are shown in Fig. 3.13.

The influence of EDF is not taken into account since only the PMF is heated here. The birefringence of the PMF reduces as the temperature increases. With the increase of temperature from 30°C to 60°C, the birefringence reduction dominates the fiber elongation, thus the resonance peaks are firstly blue-shifted as the resonant wavelength is determined by the product of birefringence B and fiber length L . When we increase the temperature further to 90°C, the fiber elongation effect will be dominant, so the transmission peaks experience a red shift. We obtain 16pm/°C and 12pm/°C temperature coefficient for lasing wavelength from 30°C to 60°C and 60°C to 90°C respectively. The temperature coefficient of the fiber laser is reduced to nearly one third of the first setup because the length of PMF used here is much shorter than the 15m PM-EDF. However, the channel spacing variation with temperature obtained is even increased from 0.5pm/°C to ~2.3pm/°C. The degradation of the stability is due to the increased channel spacing from 0.67nm in PM-EDF to 1.3nm.

Such large temperature coefficients for the previous two setups will limit the practical applications of the fiber laser as a reliable light source. Taking advantage of the high

birefringence and the low temperature sensitivity of the HiBi-PCF, a new EDFL as shown in Fig. 3.14 is demonstrated here. The 4.8m PMF in the second setup is now replaced with 4.8m HiBi-PCF from *Crystal Fibre*. The scanning electron micrograph of the HiBi-PCF is shown as an inset of Fig. 3.14. The birefringence B was measured to be 8.65×10^{-4} at 1550nm. Two ends were spliced to the EDF and SMF. Mode field diameters at the two orthogonal polarization axes of the PCF are $3.6\mu\text{m}$ and $3.1\mu\text{m}$, and the mode field difference will cause a large coupling loss. The PCF to SMF splicing loss is about 3dB, which increases the cavity loss of the MWFL up to around 18dB. Two counter-propagating light waves travel along different axes of the HiBi-PCF by setting the polarization controller in the loop; the PC was set to generate a 90 degree rotation to the polarization state of the light going through it in both directions.

Figure 3.14: Schematic diagram of third setup of the proposed MWFL.

From Fig. 3.15, we observe that multiple lasing lines are generated between 1560nm and 1564nm, with equal wavelength spacing. The wavelength separation between two lasing lines is about 0.6nm, which agrees well with the theoretical value of the channel spacing 0.59nm calculated from Eq. (3.5). The optical power of all lasing lines is about 0.3mW and relatively flat output powers of all the lasing wavelengths are observed. By changing the setting of the polarization controller within the laser

cavity, the losses in two polarization states also change, so loss and gain balancing can be achieved with more lasing wavelengths. The full-width-half-maximum (FWHM) linewidth of each lasing line is less than 50pm, which is limited by the resolution of the optical spectrum analyzer (OSA) with the resolution set as 0.1nm. Fig. 3.15 (b) shows simultaneously three lasing lines at 1561.6 nm, 1562.2nm, and 1562.8nm. Fig. 3.15 (c) shows that four lasing lines can be simultaneously obtained by carefully adjusting the polarization controller. The signal-to-noise ratio (SNR) of all these lasing lines is very large (over 30dB). And all these lasing lines have an optical power greater than 100 μ W.

Figure 3.15: Output spectrum of the fiber laser at different setting of the polarization controller: (a) two lasing lines; (b) three lasing lines; (c) four lasing lines.

When the temperature of the HiBi-PCF is increased, the fiber will elongate and the birefringence will vary due to the thermal expansion. We have found that the channel spacing increased with a $0.05\text{pm}/^\circ\text{C}$ temperature coefficient for the HiBi-PCF based Sagnac loop, which matches well with the results reported [107]. Transmission spectra at different temperatures are shown in Fig. 3.16. The transmission peaks as well as the channel spacing change with temperature variation. The channel spacing is reduced because of the slight elongation of the PCF. Most distributed feedback (DFB) lasers show a wavelength sensitivity with respect to temperature of about $2\text{pm}/^\circ\text{C}$ [122]. In case of the HiBi-PCF based Sagnac loop, the shift of the center wavelength with temperature can reach approximately $2\text{pm}/^\circ\text{C}$.

Figure 3.16: Transmission spectra as a function of temperature for the HiBi-PCF based fiber laser.

The comparison of the temperature stability for three setups in this section is shown in Table 3.1. The stability of the lasing wavelength is determined by the polarization coupling ratio at a fixed polarization controller setting, which makes the HiBi fiber in the Sagnac loop a key component for the temperature sensitivity. The resonance wavelength λ and the channel spacing $\Delta\lambda$ are both related to the product of birefringence B and fiber length L , where L increases with the operating temperature. The fiber core of a panda PMF is GeO_2 doped, while the PCF is made of silica only. For the HiBi-PCF, the fiber elongation (ΔL) with an increase in temperature will be smaller compared with that of the normal PMFs. When the birefringence is stress-induced, the doping area has a strong temperature dependence because of its higher temperature coefficient ($6.1 \times 10^{-6}/^\circ\text{C}$) compared with pure silica ($0.55 \times 10^{-6}/^\circ\text{C}$) [123]. The thermal expansion coefficient is more uniform in the two orthogonal directions of PCF, so its birefringence is relatively stable with temperature. Furthermore, due to the large birefringence of HiBi-PCF, the length of the birefringent component is much shorter than using normal PMF. Thus, the temperature sensitivity of the EDFL system influenced by the variation of BL product is much smaller for a PCF based Sagnac loop.

	PM-EDF	EDF & PMF	EDF & HiBi-PCF
$\delta(\Delta\lambda)/\delta T$	0.5pm/ $^\circ\text{C}$	0.25pm/ $^\circ\text{C}$	0.05pm/ $^\circ\text{C}$
$\delta\lambda/\delta T$	46pm/ $^\circ\text{C}$	12pm/ $^\circ\text{C}$	2pm/ $^\circ\text{C}$

Table 3.1: Comparison of temperature stability in three setups of MWFL.

3.4 Conclusions

In this chapter, we have designed index-guiding and bandgap-guiding HiBi-PCF structures. Both structures deploy the elliptical lattice in the cladding, for achieving a high birefringence up to 10^{-3} at 1550nm. This birefringent property is induced by the reduced rotational symmetry due to the elliptical air-holes/rods in the cladding. Moreover, the high index contrast between defects and background material also plays a part in providing the high birefringence in the fibers. We have applied a section of HiBi-PCF into a Sagnac loop and demonstrated the temperature-stability improvement of a multi-wavelength fiber laser (MWFL). Due to the uniform material of the PCF, we achieved 0.05pm/°C thermal coefficient for the channel spacing of the MWFL, which is a ten fold improvement compared with that using polarization-maintaining erbium-doped fiber (PM-EDF). The lasing wavelength variation with temperature can be reduced to 2pm/°C, which is comparable to the standard DFB laser.

4 Dispersion-Compensating PCF

4.1 Introduction

If applications of microstructured PCFs are expected to be deployed within the optical communication area, not only the birefringence as discussed in the previous chapter, but also the dispersion tailoring will be one of the interesting and challenging research directions. In this chapter, dispersion characteristics of PCF are explored in various perspectives, such as ultra-high dispersion, ultra-flattened dispersion. Novel structures for dispersion-compensation will be proposed.

The group velocity associated with the fundamental mode of a fiber is frequency dependent. As a result, different spectral components of the pulse travel at slightly different group velocities. This phenomenon is referred as group velocity dispersion (GVD) or simply dispersion. In a WDM communication system, a uniform response of the spectral components highly depends on the flatness of the dispersion curve. Meanwhile, the amount of 20ps/km-nm chromatic dispersion in SMF will limit the data transmission rate. Thus, control of dispersion is very essential for supporting short pulse propagation and the dispersion needs to be compensated by a special fiber with a large dispersion of opposite sign. So far, much research work has been contributed to the analysis of dispersion related designs using PCFs [124]-[134]. The

microstructures can be tailored to exhibit special modal properties due to a strong dependence function on wavelength for the cladding. Very small dispersion values and near-zero dispersion slope over C-band and L-band could be achieved. Ultra-flattened dispersion was obtained where the slope could be as small as 0.005ps/km-nm^2 . Zero dispersion wavelength could be shifted with the variation of the air-filling fractions [126] [128]. The idea of using PCF to compensate dispersion was initialized from the idea in [135]. The propagation constant for PCF can only be calculated from numerical methods and this process is usually time-consuming and computational sophisticated. Thus Birks *et al.* used a simplified model and they approximated the microstructure by a silica core in air. However, the simplified model might not be applicable for dispersion compensation design. Rather they provided a qualitative study only. Shen *et al.* improved the model by considering the microstructured cladding and normal dispersion up to -474.5ps/km-nm was achieved in their PCF structure [136]. In this chapter, we used the BPM to calculate the mode propagation for obtaining the dispersion characteristics, which is a proper choice by considering computational efficiency and accuracy. Moreover, it can handle loss problems.

4.2 Dispersion Tailoring in PCF

4.2.1 Dispersion Tailoring in Standard PCF

The hexagonal-latticed PCF waveguide shown in Fig. 4.1 is used for various modeling. The diameter of the air-holes (d) and the center-to-center distance between adjacent air-holes (Λ) are two main parameters used to define different waveguides. The light confinement is due to many inclusions in a silica matrix rather than a single

doped region, the degree of freedom is larger than that in conventional fiber. Dispersion characteristics are derived from the quantitative derivation of waveguide dispersion $D_g(\lambda)$ and material dispersion $D_m(\lambda)$ [137].

$$D(\lambda) = D_g(\lambda) + D_m(\lambda) \quad (4.1)$$

The waveguide dispersion describes the contribution of fiber design parameters such as core radius and core-cladding index difference. The material dispersion accounts the variation of refractive index with wavelength and it can be calculated from the Sellmeier equation [38] [138]:

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (4.2)$$

where the values for the six coefficients in the equation are listed:

Coefficient	Value
B_1	1.03961212
B_2	$2.31792344 \times 10^{-1}$
B_3	1.01046945
C_1	$6.00069867 \times 10^{-3} \mu\text{m}^2$
C_2	$2.00179144 \times 10^{-2} \mu\text{m}^2$
C_3	$1.03560653 \times 10^2 \mu\text{m}^2$

This total chromatic dispersion can also be directly approximated from the modal effective index of the fundamental mode over a range of wavelength [139].

$$D(\lambda) = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2 \approx -\frac{c}{\lambda} \cdot \frac{d^2 n_{eff}}{d\lambda^2} \quad (4.3)$$

where β_1 and β_2 are the first order and second order propagation constants, c is the velocity of light in vacuum and λ is the operating wavelength. Since the effective index n_{eff} of PCF is a strong function of wavelength, the variation of dispersion might

be scalable to extremely small or large values. By tuning the arrangement of the air-holes, flattened dispersion can be achieved from $1.3\mu\text{m}$ to $1.6\mu\text{m}$ as shown in Fig. 4.2. A dispersion slope smaller than 0.01ps/km-nm^2 is theoretically obtained if $d/\Lambda=0.30$, $\Lambda=2.3\mu\text{m}$. The result agrees well with the literature and such structure will be potentially useful in ultrawide-band WDM applications [174]. To obtain an acceptably smooth dispersion curve, we have to increase the number of calculated effective index with respect of wavelength (Fig. 4.2 takes ~ 10 minutes).

Figure 4.1: Cross-Section of a hexagonal-latticed PCF with a defect in the center.

Figure 4.2: GVD for PCF with $d/\Lambda=0.30$, $\Lambda=2.3\mu\text{m}$.

4.2.2 Dispersion Tailoring in Interstitial-Hole PCF (IH-PCF)

In actual fabrications, interstitial holes would be formed after the stack and drawing process. Special pressure control may be required to eliminate these interstitial holes. Some interesting initial work taking advantage of these tiny hole have been done in PBGF to broaden the photonic bandgap [140]. We extend and complete the theoretical analysis of similar structures in index-guiding PCFs. And we name it IH-PCF. Interstitial holes are also located in the gaps of capillaries as shown in Fig. 4.3 (a). The defining parameters are the physical pitch (distance between the neighboring air-holes) Λ , the diameter of the air-hole centred in the unit cell d , and the diameter of the interstitial air-hole p . The size of the interstitial holes varies with the stress in the drawing process. The unit cell in the cladding is shown in Fig. 4.3 (b). The interstitial hole in the gap of three capillaries is shown in Fig. 4.3 (c).

Figure 4.3: (a) Lattice design of IH-PCF. (b) Hexagonal unit cell for the IH-PCF. (c) Interstitial hole.

Figure 4.4: Chromatic dispersion of IH-PCFs with different interstitial air-hole size.

The chromatic dispersion is directly calculated from the effective index of the fundamental mode according to Eq. (4.3). We compare the chromatic dispersion in Fig. 4.4 for $p=0.10\Lambda$, 0.13Λ , and 0.15Λ , where $\Lambda=4\mu\text{m}$, $d=2\mu\text{m}$. We have observed that the zero dispersion is shifted to the shorter wavelength by increasing the size of interstitial holes. It has been proven by literature [129] [137], the zero dispersion can be shifted to shorter wavelength with the increase of air-filling fractions. Furthermore, since the NA ($n_c^2 - n_{cl}^2$), will be larger for our IH-PCF, the cutoff wavelength will thus be shifted to longer wavelength compared with a standard PCF.

p	Imaginary (n_{eff})	Loss
0	3.448×10^{-8}	1.21 dB/m
0.1Λ	1.082×10^{-8}	0.38 dB/m
0.105Λ	2.052×10^{-9}	0.07 dB/m
0.1133Λ	2.881×10^{-10}	0.01 dB/m

Table 4.1: Confinement loss for IH-PCF with different interstitial air-hole sizes.

Figure 4.5: (a) Grey region is the gaps between the capillaries in a standard PCF. (b) Grey region is the equivalent interstitial air-hole.

Not only the degree of freedom in tailoring the zero dispersion wavelength is enhanced by the assistant interstitial holes, the mode is also more tightly confined because of the larger air-filling fractions [141]. Confinement loss is an additional form of loss that occurs in single-material fibers which is determined by the geometry of the waveguide structure. With the increase of the air-filling fraction in PCF, the light leakage to the cladding will be reduced. It can be calculated from Eq. (2.10). The imaginary part of the effective mode index will decrease correspondingly and the confinement loss will reduce proportionally. We can expect the confinement loss will be reduced significantly by increasing the size of the assistant interstitial holes. As shown in Table 4.1, at $\lambda=1.55\mu\text{m}$, $d/\Lambda=0.5$, number of air-hole rings N is 3, the confinement loss for a PCF without interstitial holes is 1.21dB/m. After employing the interstitial holes with diameter 0.1133Λ , the confinement loss is reduced to 0.01dB/m, which is a significant improvement. We choose the interstitial air-hole size that has equivalent area as the gap regions between three identical capillaries, that is

$p_{max}=0.1133\Lambda$. The evolution of this maximum interstitial air-hole size is shown in Fig. 4.5.

Figure 4.6: Fiber cross-sections and effective mode distribution: (a) standard PCF (b) IH-PCF.

Because the effective air-filling fraction of the inner air-hole rings will influence more on the confinement, the existence of interstitial holes effectively blocks the leakage through those silica bridges as illustrated in Fig. 4.6. Correspondingly, the effective mode area A_{eff} [138] is calculated with:

$$A_{eff} = \frac{(\iint |E(x, y)|^2 dx dy)^2}{\iint |E(x, y)|^4 dx dy} \quad (4.4)$$

where $E(x, y)$ is the modal distribution for the fundamental mode in the transverse direction. The effective mode area is $20.3\mu\text{m}^2$ for a standard PCF without interstitial air-holes ($d=2\mu\text{m}$, $\Lambda=4\mu\text{m}$, $\lambda=1.55\mu\text{m}$). With the assistance of the tiny holes, the effective area is reduced to $12.1\mu\text{m}^2$. The evolution of the mode distributions is

illustrated in Fig. 4.6. Since the nonlinear coefficient is inversely proportional to effective area A_{eff} , the nonlinear factor will be increased by 50% with the interstitial air-holes.

4.3 Design of DC-PCF

4.3.1 Introduction

Fiber with a large normal dispersion value at 1550nm wavelength can be very useful for compensating anomalous dispersion contributed by transmission fibers currently deployed in communication systems. It was shown that highly negative dispersion value is achievable with a large refractive index contrast. However, with high value of index contrast, the scattering loss will also increase leading to the deployment of erbium-doped amplifiers (EDFAs) along with the dispersion compensating fiber (DCF) [142]. DCF design using W-shaped index profile in conventional fiber was proposed in [143]. The basic idea is to form a dual concentric-cores structure so that the mode distribution can be coupled from the inner core to the outer core. Thyagarajan *et al.* have shown a concentric-core DCF which is capable to provide dispersion values about -5000ps/km-nm.

4.3.2 Design of Circular-Hole DC-PCF

Similarly we can easily design a dual concentric core structure by using the flexible microstructure of PCF. The cross section view of our proposed DC-PCF is shown in Fig. 4.7 (a). The waveguide has two cores: the inner one is formed by the central

doped silica region, which is surrounded by bigger air-holes shown in Fig. 4.7 (b); the outer one is formed by taking away the third layer of air-holes from a periodic triangular holey structure as illustrated in Fig. 4.7 (c). The parameters for the design are: $\Lambda=4.16 \mu\text{m}$, $d_{big}/\Lambda=0.71$, $d_{doping}/\Lambda=0.71$, $d_{small}/\Lambda=0.3$. The background index of fused silica is 1.45, and the central dashed circle denotes a doped region with a refractive index of 1.462. The parameters of the two cores are so chosen that each of them independently supports a single azimuthally symmetric propagation mode at the desired wavelength, $\lambda=1550\text{nm}$ in our case.

Figure 4.7: Cross-sections of (a) the proposed DC-PCF; (b) separated waveguide with inner core; (c) separated waveguide with outer core.

The refractive index profile of the proposed DC-PCF design is shown schematically in Fig. 4.8: the inner core with a large refractive index difference and the outer core with a small difference. The effective indices of two concentric-cores are chosen for the two cores to support single azimuthally symmetric propagation modes at 1550nm independently. During the design process, we can separate the proposed

superstructure into two structures and treat them independently. By calculating the effective index of the fundamental mode for the two separated structures, we change the hole size or doping factors until the two index-curves have a crossing near $\lambda=1.55\mu\text{m}$.

Figure 4.8: Refractive index profile of the proposed DC-PCF along the radial distance in x-direction.

Effective fundamental mode indices as a function of wavelength are plotted in Fig. 4.9 for three waveguides described in Fig. 4.7. It is clearly shown that the two curves for inner core mode and outer core mode cross each other around 1550nm wavelength. This crossing suggests that the super-mode, which is the fundamental mode for the waveguide in Fig. 4.7 (a), will transit from inner core mode to outer core mode (where the coupling of mode from inner core to outer core has been shown in the inset of Fig. 4.9) at that wavelength point, as indeed depicted by dots in Fig. 4.9. This abrupt change in effective index for our super-mode will give rise to a very large dispersion

value since dispersion is calculated as the second derivative of the effective index as explained by Eq. (4.3).

Figure 4.9: Effective-index curves for three waveguides described in Fig. 4.7.

(b)

Figure 4.10: Chromatic dispersion of (a) proposed DC-PCF with circular air-holes (b) DC-PCF when we change the pitch size.

Dispersion for the proposed waveguide is shown in Fig. 4.10(a). It shows a dispersion value at $\lambda = 1.543 \mu\text{m}$ over -6000 ps/km-nm . The computation for such a defective fiber problem will be demanding ($\sim 3 \text{ min}$ for a single wavelength). Consequently, effective indices at a small number of wavelength points are computed. Should we increase the computation resolution, the dispersion curve shown in Fig. 4.10(a) may change a little bit in shape, nevertheless, the dispersion curve gives a very good qualitative picture. Simulation results in Fig. 4.10(b) show that the minimum chromatic dispersion value is more negative and the full width at half maximum value is narrower when the pitch size decreases. This is because smaller pitch size results in fictitious reduction of central core size which makes the microstructure more dispersive.

We have presented a novel design of DC-PCF in this section. It deploys the concept of mode coupling from inner to outer structure with a matched cladding which is similar to the conventional W-shaped DCF. The effective mode index profile can be easily tuned by varying the microstructure. This helps to solve the problems of doping limitation and nonlinear effects induced by small core design. Such fiber with large negative dispersion can effectively compensate anomalous dispersion accumulated by transmission fibers currently deployed in communication systems.

4.3.3 Design of Elliptical-Hole DC-PCF

Figure 4.11: Waveguide dispersion for PCF with different ellipticity.

In a typical optical communication system, it will be useful to make the DCF itself polarization maintaining. The polarization maintaining property can be easily realized in PCF structures because we can change the shape and arrangement of air-holes.

Similar design principles shown in the previous section can be extended to a PCF structure with elliptical air-holes. For a microstructured cladding with identical air-holes discussed in Chapter 3, we understand that the birefringence of such PCF is mainly determined by the most inner two layers of elliptical air-holes. A PCF with $r=d_x/d_y=0.5$ can achieve birefringence up to 0.85×10^{-3} . Moreover, by varying the ellipticity of the air-holes, flattened waveguide dispersion can be achieved in a wide range of wavelength from $1.3\mu\text{m}$ to $1.6\mu\text{m}$ with a dispersion slope of 0.01ps/km-nm^2 only. The calculation results using the numerical method BPM are shown in Fig. 4.11. The relatively flat dispersion curves indicate such fiber ($N=4$, $\Lambda=2.3\mu\text{m}$) can be utilized for ultra-broadband applications [174].

Figure 4.12: Schematic of the (a) superstructure; (b) inner-core waveguide structure; (c) outer-core waveguide structure.

By taking advantage of the degree of freedom in designing the air-hole size and arrangement, we proposed a DC-PCF with elliptical air-holes to achieve high birefringence and large negative dispersion at 1550nm wavelength. This design is

expected to be promising for dispersion compensation in a polarization maintaining transmission system. The cross-section of the super-structure and the two separate cores are shown in Fig. 4.12: The inner core is a doping area with $n_{innercore}=1.462$, the outer core is composed of pure silica layer. The major axis is directed along the y-axis. A_1 is elliptical air-hole area in the outer cladding: $A_1=\pi 0.1764\Lambda^2$. A_2 is the elliptical-hole area in the outer core: $A_2=\pi 0.005\Lambda^2$. A_3 is the elliptical-hole area in the inner cladding and the central doping region: $A_3=\pi 0.125\Lambda^2$.

Effective mode indices as a function of wavelength are plotted in Fig. 4.13 for the inner core and outer core respectively. Solid curve corresponds to the effective mode index of the inner doped core, the dashed curve corresponds to the effective mode index of the outer pure silica core, and the dotted curve corresponds to the effective index of the super-mode. It is clearly shown that the two index-curves for inner core mode and outer core mode cross each other around $\lambda=1550\text{nm}$, which suggests the existence of a pair of super-modes at this wavelength. From reference [143], we find that the two super-modes are symmetric, thus analyzing one is sufficient to illustrate the dispersion compensation characteristics of such design. By zooming into the wavelength close to the cross-point and calculating the fundamental mode of the superstructure, we can observe the coupling of mode from inner-core to outer-core. The behavior of the fundamental mode is the same as the one in the previous section: at wavelength before the crossing point, the field is essentially confined in the inner core, after this crossing point, most of the fundamental mode field is coupled to the outer core. This abrupt change in effective index for our super-mode will give rise to a very large dispersion value, which is calculated as the second derivative of the effective index.

Figure 4.13: Effective-index curves for three waveguides described in Fig. 4.12.

Figure 4.14: Chromatic dispersion of proposed DC-PCF with elliptical air-holes.

Dispersion for the proposed waveguide is shown in Fig. 4.14. It shows dispersion value at $\lambda=1550\text{nm}$ is nearly -6000ps/km-nm . The elliptical holes are used in the design simply for inducing the large birefringence. Thus the variation of dispersion characteristic will be similar to that we have obtained in DC-PCF with circular air

holes. Such as the minimum dispersion value will become more negative and the 3dB bandwidth will be narrower if the air filling fraction increases, because the increase of air filling fraction results in fictitious reduction of central core size. Elliptical structures have already been proven to be realizable in fabrication [110]. The higher refractive index of the central core can be realized by doping Germanium since the maximum index difference that can be obtained is 1.23%. The mode field diameter is comparable with SMF in conventional fiber systems, so the splicing loss will not be uncontrollable due to the mode mismatching. By combining the novel dispersion characteristic and the high birefringence induced from the elliptical holes, we expect this structure to be promising for dispersion compensation application in a polarization maintaining optical system.

4.4 Conclusions

In summary, we have investigated and analyzed the dispersion characteristics of PCFs. The dispersion controlling and tailoring in a standard PCF and an interstitial-hole assistant PCF has been theoretically demonstrated. A significant shift of zero dispersion wavelengths has been observed with the variations of air-filling fractions. We have proposed a concentric-core PCF design that exhibits a negative dispersion as large as -6000ps/km-nm at 1550nm for effective dispersion compensation. And we have extended the idea of mode coupling between two concentric-cores into a structure with elliptical air-holes. Similarly large negative dispersion has been achieved. These results indicate the interesting potential for dispersion compensation or dispersion management in optical communication systems. Nevertheless, increasing the bandwidth for dispersion compensation requires more complicated fiber design, thus the fabrication process will remain challenging.

5 Two-Core PCF

5.1 Introduction

Chapter 3 and chapter 4 have focused on designing PCF structures to achieve high birefringence and dispersion tailoring. These properties are essentially useful for transmission systems. Moreover, PCF can be a potential candidate for fiber devices, such as two-core fiber based directional couplers. This chapter will discuss the design, fabrication and analysis of two-core PCFs.

Multi-core conventional fibers have driven many research interest and device applications [144-148]. Many useful devices based on a symmetric two-core fiber can be realized, such as directional couplers, wavelength division multiplexers, and polarization beam splitters etc. Taking advantage of the air-holes in PCFs, such microstructures have initiated many applications based on multi-core structures [71] [130] [149]-[157]. For two-core PCFs, much work has been presented on the numerical calculation of beat length. Several designs were theoretically analyzed in [149]-[150] and [158], but these numerical modeling were computationally inefficient and the experimental confirmations remain sparse. Moreover, the mode coupling in these two-core structures has not been systematically studied in detail as that in

conventional fiber. In [154], the wavelength dependence of the coupling coefficient could not be obtained from the experiment directly and the experiment was only demonstrated to verify the theoretical work. Furthermore, a strong asymmetry existed which is not desired for general applications.

In this chapter, we will investigate two-core PCF structures both theoretically and experimentally. An effective index based coupled mode theory and an expansion method based super mode theory will be built up for the modeling of two-core PCFs. The detailed fabrication process will be presented for both silica and polymer materials. Measurement of coupling effects in structures with closely-adjacent and far-separated two-cores will be demonstrated in order to compare the wavelength dependence of the beat length.

5.2 Theory for Two-Core PCF

5.2.1 Coupled Mode Theory in Two-Core Fiber

In a standard optical fiber, most light can be confined in the high refractive index core region by means of total internal reflection. There will be certain amount of evanescent field in the transverse direction that extends into the low-index region. If another high refractive index region is placed near enough, the evanescent can couple into that region. The mode coupling in a “single-mode” two-core fiber leads to the optical power to be transferred back and forth between the two parallel cores, and this phenomenon can be modeled with the coupled mode theory [144]-[145] [159]-[160]. Coupled mode theory for two parallel waveguides is an approximate formulation in

which the guided modes of the entire waveguide are represented as linear combination of the guided modes in the individual waveguides. The first work to provide a generalized framework for the use of coupled mode theory in the fiber cores appeared in 1972 [161]. The coupling can be described by the coupled mode equations [38]:

$$\frac{dE_1(z)}{dz} = i\beta_1 E_1(z) + iC_{12}E_2(z) \quad (5.1a)$$

$$\frac{dE_2(z)}{dz} = i\beta_2 E_2(z) + iC_{21}E_1(z) \quad (5.1b)$$

where E_1 and E_2 are the single-mode field amplitudes, β_1 and β_2 are the propagation constants of the fundamental mode in core 1 and core 2 respectively, as shown in Fig. 5.1.

Figure 5.1: Cross-section of a two-core fiber. R is the core radius, S is the core-to-core distance, n_{cl} is the cladding index. n_1 and n_2 are the core indices.

The coupling coefficient C_{12} or C_{21} is a measure of the overlap of fundamental modes in core 1 and core 2. The general form of the coupling coefficient is presented as:

$$C_{12} = \frac{\omega}{2} \int_{A_2} (\varepsilon_2 - \varepsilon) \cdot e_1 \cdot e_2 dA \quad (5.2a)$$

$$C_{21} = \frac{\omega}{2} \int_{A_1} (\varepsilon_1 - \varepsilon) \cdot e_2 \cdot e_1 dA \quad (5.2b)$$

where both fields are at frequency ω , $(\varepsilon_2 - \varepsilon)$ is the difference between the dielectric constants of core 2 and its cladding, and $e_1(x, y)$ is the transverse electric field profile of the fundamental mode in core 1 without the existence of core 2, $e_2(x, y)$ is the transverse electric field profile of the fundamental mode in core 2 without the existence of core 1. This integral is performed in the plane perpendicular to the fiber axis. In general, the coupling coefficients between the two cores are not equal due to the imperfect fabrication. Here we assume the two cores are identical. Thus for “single-mode” two-core fibers with identical cores, Eq. (5.2) can be simplified to be [161]:

$$C = C_{12} = C_{21} = \sqrt{2\Delta} \frac{u^2}{RV^3} \frac{K_0(wS/R)}{K_1^2(w)} \quad (5.3)$$

where S is the core to core separation between the two cores, R is the radius of the core, V is the normalized frequency, which is given by $V = k_0 R n_{co} \sqrt{2\Delta}$ and Δ is the refractive index difference between the core and the cladding, which is defined as: $\Delta = (n_{co}^2 - n_{cl}^2) / 2n_{co}^2$, n_{co} and n_{cl} are the refractive indices of the core and cladding, respectively. The parameter u is a solution of the characteristic equation:

$$uJ_1(u)/J_0(u) = wK_1(w)/K_0(w) \quad (5.4)$$

where $w^2 = V^2 - u^2$, J_0 and J_1 denote zeroth and first order Bessel functions of the first kind, and K_0 and K_1 are zeroth and first order modified Bessel functions of the second kind, respectively. The guided mode inside the high refractive index core region is described by the Bessel function. The portion in the lower refractive index cladding region is described by the modified Bessel function.

If the waveguide regions are cylindrically symmetric about the energy propagation direction, the single-mode propagation constant β_i is given by:

$$\beta_1^2 = (k_0 n_1)^2 - (u / R_1) \quad (5.5a)$$

$$\beta_2^2 = (k_0 n_2)^2 - (u / R_2) \quad (5.5b)$$

where k_0 is the free-space wave number. R_1 and R_2 are the radius of core 1 and core 2. n_1 and n_2 are the indices of core 1 and core 2.

Another important parameter to describe the coupling strength in a two-core fiber is the beat length L_c which is the shortest length required for maximum power transferring from one core to the other and back to the first core again:

$$L_c = \frac{\pi}{C} \quad (5.6)$$

If core 1 is excited with unit power and core 2 with zero power, the solutions to the coupled-mode equations (5.1) in a lossless medium will be:

$$|E_1(z)|^2 = 1 - \sin^2(Cz) \quad (5.7a)$$

$$|E_2(z)|^2 = \sin^2(Cz) \quad (5.7b)$$

5.2.2 Coupled Mode Theory in Two-Core PCF

Figure 5.2: (a) Cross-section of a two-core PCF, the transverse mode profile shown with the contour map. (b) Cross-section of the equivalent two-core fiber.

Since coupled mode theory is a well-developed theory which can have an analytical solution for the modes, we would like to deploy it into PCF structures as long as we can find equivalence between such microstructure and conventional fiber. In case of the two-core PCF structure as shown in Fig. 5.2 (a), where Λ is the hole-to-hole lattice distance, d is the air-hole diameter, S is the separation between the centers of two cores and the background material is fused silica with the refractive index 1.45. Coupled mode theory in a conventional two-core fiber has been systematically investigated in section 5.2.1, thus we use the effective index method (EIM) to get the equivalent step index profile of our two-core PCF.

The fundamental space-filling mode [162] of the infinite periodic cladding is calculated firstly and the whole periodic space is divided into hexagonal unit cells. The equivalent structure is obtained as shown in Fig. 5.2 (b) where the effective space

filling mode index of the cladding acts as refractive index of the homogenous cladding material and pure silica acts as core. R is the equivalent core radius and strongly depends on the microstructure. We calculated the fundamental mode of two-core PCF and the equivalent two-core fiber, and the same effective mode index for both structures is achieved by setting the equivalent core radius R . An analytical expression of the effective core radius has been shown recently [163]:

$$R = c_1 \Lambda / \left\{ 1 + \exp\left[\left(\frac{d}{\Lambda} - c_3\right) / c_2\right] \right\} \quad (5.8)$$

where c_1 , c_2 and c_3 are 0.686064, 0.265366, and 1.291080, respectively. This EIM is used here to build up a simple and straightforward model, and we name it effective index coupled mode theory. In this section, we use a simple structure to demonstrate the coupled mode theory in a PCF: the two separate cores are identical, lossless and monomode. The generalized analysis for non-identical, multi-mode cores will be similar to conventional structures with homogeneous cladding, which has been presented in [147].

Eq. (5.3) and Eq. (5.4) cannot be solved analytically, so we need to use numerical methods to calculate the coupling coefficient. The accuracy of the coupling coefficient depends on the modal parameters of the fiber, u and w from the characteristic Eq. (5.4). The accuracy of these two parameters depends on the accurate calculation of core index n_{co} , cladding index n_{cl} and the effective core radius R . However, n_{co} is fixed as the fused silica index 1.45. R depends on the air-filling fraction of the microstructure according to Eq. (5.8), which indicates that R strongly depends on n_{cl} . So we can conclude that the accuracy of coupling coefficient depends on the accurate calculation of effective cladding index. The sensitivity of coupling

coefficient to cladding index is shown to be around $3.55\text{m}^{-1}/0.1\%$, as shown in Fig. 5.3.

Figure 5.3: Sensitivity of coupling coefficient to the effective cladding index.

Among various numerical modeling methods, finite element method (FEM) is proven to be the most accurate method. However for the complex holey structure in PCF, the number of mesh will increase dramatically and the computational efficiency is rather poor [133] [164]-[165]. Here we employ the EIM, which is proven to be the simplest and efficient. The unit cell of the periodic microstructure in the cladding is treated as a single waveguide. The effective modal index of the unit cell is obtained as the effective cladding index value of the corresponding PCF (<2 minutes for 20 points). Then we compare with the results with that from FEM. In Fig. 5.4 (a), we compare effective cladding index calculated by EIM (solid line) and FEM (shaped mark), from top to bottom, d/Λ ratio are listed as 0.40, 0.45, 0.50, 0.55. Fig. 5.4 shows that the discrepancy of the effective cladding index between two methods is rather small for a large wavelength range. As is well known, the accuracy will increase even more when

we increase the air-filling fraction because the modes will be tightly confined in the core.

Figure 5.4: Comparison of effective cladding index of PCF (a) at different wavelength; (b) with different air-filling fractions.

To further demonstrate the validity of this effective index model, we calculate the coupling coefficient based on Eq. (5.3), and compare it with the published results [150]. In this reference, beat length L_c rather than the coupling coefficient C was calculated based on FEM. The beat length values calculated from both methods are compared in Fig. 5.5. When the fiber core size is smaller than wavelength, the coupled mode theory will not be valid any more. Thus we observed a relatively large discrepancy at small Λ . However, the difference in L_c values calculated by FEM and effective index model is diminishing when the scaling parameter Λ is increased. Therefore, the established effective index coupled mode theory is sufficiently accurate for illustrating the mode coupling properties of the most structures, and it improves the efficiency dramatically.

Figure 5.5: Comparison of coupling length calculated by EIM and FEM.

For the equivalent two-core structure of PCF, core-to-core distance S , effective core radius R and effective cladding index n_{cl} are the three principle parameters to control the coupling coefficient. In PCFs, decreasing the air-hole size is equivalent to decreasing core to cladding index contrast (while fixing the pitch size constant). This increases the coupling coefficient significantly as shown in Fig. 5.6. If the air-hole size is fixed, increase of the pitch size will cause the increase of core size, the core-to-core distance and the effective cladding index. Thus the coupling coefficient will increase as well. The coupling coefficient in a conventional two-core fiber should be strongly wavelength-dependent as calculated in Ref. 147, however spectral response in the case of two-core PCF shows a less wavelength dependence than normal two-core fiber. This can be explained from Eq. (5.2): dielectric constant of the cladding in

PCF decreases when we increase wavelength, this effect suppress certain wavelength dependence of C .

Figure 5.6: (a) Coupling coefficients evolution with wavelength: $\Lambda=4\mu\text{m}$. From top to bottom, $d/\Lambda=0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6$; (b) Coupling coefficients evolution with air-hole size: $\lambda=1.55\mu\text{m}$.

5.2.3 Super Mode Theory in Two-Core PCF

The ratio d/Λ can be designed to be very large in Fig. 5.2 (a), providing a large air-filling fraction. Then the effective index difference between the core and cladding will no longer satisfy the weakly guiding assumption, so the conventional coupled mode theory will not be valid. The effective index of the microstructured cladding is a much stronger function of wavelength than the case of a conventional fiber cladding with a homogeneous material index, so we used a super mode theory to analyze the coupling characteristics of these two-core structures. The two-core waveguide is treated as a single super structure and the effective fundamental modes are obtained from a full-

vector expansion method PWM. We chose the PWM rather than a Fourier decomposition method as demonstrated in [154] because the latter requires a large number of radial steps and azimuthal Fourier components in order to search for the even and odd mode pair. The PWM method will be more efficient computationally.

Besides the silica material, there has been much research effort on the polymer material based microstructure fibers motivated by the cheaper fiber preform as well as easier fabrication. Here we will use a two-core polymer PCF structure to demonstrate the super modes properties in such microstructure. The main reason to choose super mode theory is that it is difficult to apply the weakly-guiding assumption in polymer PCFs since the index contrast between polymer and air is even larger. The refractive index of background polymer material (PMMA) is calculated from the Sellmeier equation:

$$n^2 = A_1 - A_2\lambda^2 + \frac{A_3}{\lambda^2} - \frac{A_4}{\lambda^4} + \frac{A_5}{\lambda^6} - \frac{A_6}{\lambda^8} \tag{5.9}$$

where λ is measured in μm and the values of the six coefficient are listed as:

Coefficient	Value
A_1	2.1864582
A_2	$2.4475348 \times 10^{-4} \mu m^{-2}$
A_3	$1.4155787 \times 10^{-2} \mu m^2$
A_4	$4.4329781 \times 10^{-4} \mu m^4$
A_5	$7.7664259 \times 10^{-5} \mu m^6$
A_6	$2.9936382 \times 10^{-6} \mu m^8$

(a)

(b)

(c)

Figure 5.7: (a) Cross-section (b) Even mode (c) Odd mode for structure A.

Single-circular-core fiber has degenerate HE_{11}^x and HE_{11}^y modes propagating at the same speed. When we have two cores, the rotational symmetry of the two-core is broken and the polarization effects can not be neglected. The x-polarized fundamental mode (corresponding to HE_{11}^x mode in a single-circular-core fiber) breaks into two modes: even HE_{11}^x and odd HE_{11}^x . When the two modes have a phase difference of zero (or $2N\pi$), the left core has almost zero energy due to destructive interference. Similarly if the two modes are in anti-phase, the right core has almost zero energy. These modes have slightly different propagation constants, meaning that the phase difference between the modes evolves with propagation along the fiber. For a two-core PCF with air-hole spacing $\Lambda=2.3\mu\text{m}$, air-hole diameter $d=0.8\mu\text{m}$ and core to core distance $S=\sqrt{3}\Lambda$, which corresponds to the fiber structure A in Fig. 5.7 (a), the even mode HE_{11}^x and odd mode HE_{11}^x are illustrated in Fig. 5.7 (b)&(c). The even mode has a symmetric field distribution and the odd mode has an anti-symmetric field distribution (such result takes about 10 times computational time compared with EIM). The propagation constants for both normal modes can be expressed as $\beta \pm C$, where β is the propagation constant for the fundamental mode of the fiber with a single core.

The beat length is obtained from the effective mode indices of one polarization:

$$L_c = \lambda / (n_e - n_o) \quad (5.10)$$

where n_e is the effective mode index for the even mode, n_o is the effective index of odd mode. The effective indices for the x-polarized and y-polarized even and odd modes are calculated and plotted in Fig. 5.8. The corresponding beat length for x-polarized modes and y-polarized modes are shown in Fig. 5.9. The beat length L_c has been shown to be of the form [154]:

$$L_c = Q\lambda^{-\eta} \quad (5.11)$$

where Q and η are two constants. Fitting Eq. (5.11) to the calculated beat lengths in Fig. 5.9 confirms this, and we find that for structure A the power-function dependence of the beat length to the wavelength is $L_c^x=0.01037\lambda^{-1.143}$, $L_c^y=0.01005\lambda^{-1.184}$ for the two polarizations respectively.

Figure 5.8: Effective index of the four super-modes in structure A.

Figure 5.9: Theoretical beat length for two-core PCF structure A.

We also designed a two-core PCF structure to obtain much longer beat length as shown in Fig. 5.10: $\Lambda=2.5\mu\text{m}$, $d=1.4\mu\text{m}$, $S=3\Lambda$. Similar wavelength dependent power functions were calculated for structure B and the results are shown in Fig. 5.11:

$$L_c^x=0.135\lambda^{-0.622}, L_c^y=0.133\lambda^{-0.628}.$$

Figure 5.10: Two-core PCF structure B

Figure 5.11: Theoretical beat length for two-core PCF structure B.

Comparing these calculations for structures A and B, we observed that the Q constant is more than an order of magnitude larger for structure B, and the η coefficient is decreased by nearly a factor of two. Clearly, the dramatic increase of the beat length for structure B is due to the larger separation of the two cores. By varying the air-hole size of structure A from $0.95\mu\text{m}$ to $0.8\mu\text{m}$, we observed a decrease of the beat length as shown in Fig. 5.12. The corresponding beat length dependence on wavelength is listed as:

$$\begin{aligned} d = 0.95\mu\text{m}, & \quad L_c = 0.015\lambda^{-1.23} \\ d = 0.90\mu\text{m}, & \quad L_c = 0.013\lambda^{-1.15} \\ d = 0.85\mu\text{m}, & \quad L_c = 0.011\lambda^{-1.149} \\ d = 0.80\mu\text{m}, & \quad L_c = 0.010\lambda^{-1.143} \end{aligned}$$

Figure 5.12: Theoretical coupling length for two-core PCF structure with different air-hole size: $d = 0.95, 0.9, 0.85, 0.8\mu\text{m}$, $\Lambda = 2.3\mu\text{m}$, $S = \sqrt{3}\Lambda$. Inset is the variation of constant Q and η versus air-hole diameter.

The inset in Fig. 5.12 shows constants Q and η versus the air-hole diameter d . We found that the beat length is decreasing fast with even small changes of air-hole size. The power factor η is also decreasing, which indicates that the wavelength dependence is getting weaker with a decrease in air filling fraction. Since the beat length is inversely proportional to the coupling coefficient, we can conclude that for the same air-hole arrangement structure, there appears to be a tradeoff between the coupling coefficient and the coupling coefficient dispersion (wavelength dependence).

5.3 Fabrication of Two-Core PCF

5.3.1 Fabrication of Silica Two-Core PCF

The idea of producing low-loss single material using fused silica for optical fiber technology development started in the early year of 1974 [166]. The key issue in the fabrication has always been how to obtain a fiber structure for a specific application and then maintain the shape in the fiber drawing for a long length. Traditionally, the optical fibers are fabricated from the preform and drawn in a high-temperature tower furnace [167]. However, the most common technique to fabricate PCF is to stack silica capillary tubes and solid silica rods. This method was initiated by Birks *et al.* in 1996, which is shown to be relatively fast, low-cost and flexible [168]. Fig. 5.13 shows the process of stack-and-draw process for a typical PCF structure.

Figure 5.13: The illustration of stack-and-draw process in PCF fabrication.

This part describes our attempts in fabricating a two-core PCF using fused silica in Yangtze Optical Fiber and Cables, China. The preform is prepared in order to stack a two-core fiber structure as shown in Fig. 5.14 (a). A pair of clamp is used at both sides of the stacking jacket to fix the structure. For the clamp, special designs are made in order to apply positive and negative pressures. The positive pressure is applied into the air-holes in order to maintain the holes shape during the fiber drawing. The negative pressure is applied to the air gaps between capillaries and jacket tube, as well as the small gaps between capillaries. In order to maintain the microstructure, it is necessary to fuse the capillaries and the jacket tube together.

The stacked preform is drawn in a fiber drawing tower. The drawing temperature is around 1850°C to 1900°C with a speed about 100m/min. There are two key perspectives in this process. One is the material matching between the capillaries and the jacket tube, and another is an efficient pressure control system. Stacking process requires a careful handling, and the control of air-hole size makes the drawing significantly complex. The key element is the ability of maintaining the structure of PCF preform during the PCF fabrication. The stacked capillaries were aligned vertically along the oven. The cross-section image of the fabricated silica based two-

core PCF is shown in Fig. 5.14 (b). The loss of each core is around 5dB/km at 1550nm. Based on the theoretical studies in the above section, it is interesting to conclude that by controlling the air-filling fraction and the core to core separation, the coupling coefficient may be enhanced or reduced depending on specific applications.

Figure 5.14: (a) Stack structure and (b) SEM picture of a two-core PCF.

5.3.2 Fabrication of Polymer Two-Core PCF

We have also made some efforts to fabricate similar structure using polymer (PMMA) material at Optical Fibre Technology Centre, Australia. It will be comparably easier because stacking is not required for the preform preparation. Unlike silica PCFs, which are generally fabricated by stacking capillaries to form the microstructure, the air-hole arrangement in a polymer PCF is drilled into a preform as shown in Fig. 5.15 (a) [169, 170]. The dimensions of air-holes and pitch, as well as the microstructure arrangement were keyed into a computer program to control the mechanical drilling.

Figure 5.15: (a) Preform after drilling. (b) Glued preform ready for drawing to cane. (c) Sleeving of the cane for drawing to fiber.

The two sides of the preform are then glued with two slew-driven hollow PMMA assistant preform respectively using adhesive (a good structural bond for acrylics for external applications) as shown in Fig. 5.15 (b). Then the preform goes to the cooling and drying process for days. The inside of one hollow preform is drilled to have a hole connected with the holey regions of the middle section, so that the pressure can be released inside the preform. Reflective tape is then used to cover the hollow preform so that the adhesive glue will not melt by the radiation heat in the oven. This preform is then drawn to microstructured primary cane in a primary oven ($T=160^{\circ}\text{C}$) of the

polymer fiber drawing tower. In this step, the diameter of the primary cane is reduced by ten times as shown in Fig. 5.15 (c). These canes are then put into a hollow PMMA jacket for sleeving followed by drawing to fiber in the secondary oven [169, 170].

Figure 5.16: Fabricated polymer two-core PCF corresponding to (a) structure A; (b) structure B in section 5.2.3.

In order to study the coupling characteristics between the guided modes in the two-core PCF and to verify it with the above theoretical results, we have fabricated two two-core PCF as shown in Fig. 5.16. The parameters for two-core PCF structure A are: air-hole spacing $\Lambda=2.3\mu\text{m}$, air-hole diameter $d=0.8\mu\text{m}$ and core to core distance $S=\sqrt{3}\Lambda$, the loss at 650nm is $\sim 2\text{dB/m}$. The parameters for two-core PCF structure B are: air-hole spacing $\Lambda=2.5\mu\text{m}$, air-hole diameter $d=1.4\mu\text{m}$ and core to core distance $S=3\Lambda$, the loss is around 1.5dB/m at 650nm.

Figure 5.17: Setup for testing mode properties of the fabricated two-core fiber.

After fabrication, the single mode nature of the individual cores in the fibers was tested by launching coherent light from a HeNe laser into both cores by illuminating the end of the fiber using an objective lens as shown in Fig. 5.17 [154]. A clear interference pattern at the output end of the fiber with high fringe visibility was obtained as shown in Fig. 5.17. A red-color mode field image is clearly observed in the two cores of the fiber. In addition, the mode profiles in the two cores were found to be insensitive to any bending along the two-core fiber. This confirms that each core in the PCF of Fig. 5.16 is single mode, at least from a wavelength of 633nm onwards.

5.4 Analysis of Two-Core PCF

In section 5.2, coupled mode theory and super mode theory have been applied into different two-core PCFs to model the coupling characteristics. And fabrication trials are presented in section 5.3 for both silica and polymer materials. Theoretically and experimentally we have the interest to explore the properties in two-core PCF, such as

the effectively-tunable coupling with different core separations, the strain sensitivities, as well as the wavelength dependence of the coupling coefficient.

5.4.1 Tunable Coupling

Figure 5.18: Two-core PCFs with three different core-to-core separations: (a) $S=2\Lambda$; (b) $S=3\Lambda$; (c) $S=4\Lambda$.

Arranging the position of the solid rods in the stacking process can easily change the separation between the two cores. Two-core PCF structures with different core-to-core distance are shown in Fig. 5.18, with $S = 2\Lambda, 3\Lambda, 4\Lambda$ respectively. With the increasing separation, we can expect a reduction of coupling coefficients. Calculated results are shown in Fig. 5.19, corresponding to $S = 2\Lambda, 3\Lambda, 4\Lambda$ from top to bottom respectively. The coupling coefficient is decreased by about ten times when increasing the S by one lattice distance, while keeping the same air-filling fraction by fixing the d/Λ ratio. The variation of coupling coefficients with different air-filling fraction is shown in each figure as well. The mode in each core will be more confined in the solid core region with the increase of d/Λ ratio, as well, the effective core area will decrease with the ratio increment, and thus, the coupling coefficient will be

dramatically decreased in PCF. This makes the coupling more effectively tunable compared with conventional step index two-core fiber.

(a)

(b)

Figure 5.19: Coupling coefficients of the above three structures. $\Lambda = 4\mu\text{m}$.

5.4.2 Strain-Insensitive Coupling

By evaluating the coupling characteristics in two-core PCF, we find the dependence on pitch and core diameter. These geometrical parameters can be changed by environment, such as temperature, strain or stress. For example, when stretching the fiber in the longitudinal direction, the fiber is elongated, and then the air-hole size and the pitch size are decreased. We can divide the whole microstructured cross-section into a number of hexagonal unit cells as shown in Fig. 5.2 (a): A_{hex} is the area of the unit hexagonal; A_{cir} is the area of the circular air-hole; L is the fiber length. The air-filling fraction can be calculated approximately from solid material contributing to the total mass of the fiber. By mass conservation, we can get:

$$V = (A_{hex0} - A_{cir0})L_0 = (A_{hex} - A_{cir})L \quad (5.12)$$

We assume the air-hole diameter to pitch ratio is constant since there is no temperature variation. Then $(A_{hex}-A_{cp})$ is proportional to Λ^2 , and $\Lambda_0^2/\Lambda^2=L/L_0$. The change of fiber length will also affect the strain-optic induced refractive index. This photoelastic effect also needs to be considered during the modeling, which accounts for the change of the refractive index due to the strain [171, 172]. Thus we deduced the relationship of structure change and index change under strain:

$$\frac{\Delta\Lambda}{\Lambda} = \frac{\Delta L}{2L_0} = \frac{(1-2\nu)F}{2EA} \quad (5.13a)$$

$$\frac{\Delta n}{n} = \frac{n^2 F}{2EA} (1-2\nu)(2\rho_{12} + \rho_{11}) = n^2 (2\rho_{12} + \rho_{11}) \frac{\Delta L}{2L_0} \quad (5.13b)$$

where ν is the Poisson's ratio, F is the applied strain force on the fiber, E is the Young's modulus for silica, A is the fiber cross-section, and ρ_{11} and ρ_{12} are the components for the strain-optic tensor.

(a)

(b)

Figure 5.20: Coupling coefficients of two-core PCF (a) with different fiber elongation length and different air-filling fractions: $\Lambda=4\mu\text{m}$, $\lambda=1.55\mu\text{m}$; (b) within strain limit of silica material. Both figures have insets where y-axis is in linear scale.

This strain elongation causes the decrease of core size R as well as the core-to-core separation S , and these two parameters cancel the influence of each other to the coupling coefficient. Longitudinal strain causes the re-distribution of the stress inside the material, which increases the refractive index according to the photoelastic relationship. For structures with small air-filling fractions, the index variation caused by strain in the core and cladding regions is roughly equivalent to each other. For a two-core structure made from fused silica, index variation cannot balance each other for the core and cladding when the d/Λ ratio increases, thus the photoelastic influence to the variation of coupling becomes significant. The slope of the coupling coefficient curve vs. strain is shown in Fig. 5.20 (a) and it is larger in the two-core PCF with

increased d/Λ . Since the breaking strain of silica PCFs is measured to be on the order of 1%, we consider the geometric parameter and index variations for two-core PCF under different strain conditions below the breaking threshold. We calculated the coupling coefficients, and investigated the elongation dependence of coupling characteristics, where $\lambda = 1.55\mu\text{m}$, $\Lambda = 4\mu\text{m}$, $d/\Lambda = 0.25, 0.375, 0.5, 0.625$. The ultra-flattened coupling coefficient spectrum with fiber elongation $\Delta L/L$ is shown in Fig. 5.20 (b), which shows good performance in terms of strain insensitivity ($0.6 \times 10^{-4} / \text{m} \cdot \mu\text{E}$). This very small strain sensitivity is due to the very small photoelastic constants. Meanwhile the suppression results between the index variation and the air-filling fraction will reduce the strain sensitivity as well. This is unique properties for single material silica PCF.

5.4.3 Measurement of Coupling

The beat length is defined as the required fiber length for achieving complete power transfer from one core to another and back. When light is launched into one core of the fiber, along the length of the fiber, we have the following relationships (we assume $\Delta\lambda / \lambda \ll 1$):

$$L = NL_c(\lambda) = (N+1)L_c(\lambda + \Delta\lambda) \quad (5.14a)$$

$$L_c(\lambda + \Delta\lambda) \cong L_c(\lambda) + \Delta\lambda \cdot \frac{dL_c(\lambda)}{d\lambda} \quad (5.14b)$$

$$\frac{dL_c}{d\lambda} = -\eta \cdot \frac{L_c}{\lambda} \quad (5.14c)$$

where L is the fiber length, $N = L/L_c(\lambda)$ is a real number, and $\Delta\lambda$ is the wavelength spacing between adjacent minima in the transmission spectrum of one core at the end

of the fiber. Based on the above relationships, we can derive the equation of the beat length and the wavelength spacing:

$$\frac{L_c}{L} = \eta \cdot \frac{\Delta\lambda}{\lambda} \quad (5.15)$$

Figure 5.21: Experiment setup for measuring the coupling length and corresponding wavelength dependence.

In this section, we measure the beat length of the two polymer two-core PCF structures shown in section 5.3.2. The corresponding wavelength dependence is obtained from the spectrum observed in the setup of Fig. 5.21. A broadband white light supercontinuum source consists of a Nd:YAG microchip laser at 1064nm (8.3μJ and 0.56ns per pulse, at 7.14kHz repetition rate, 6kW peak power,) coupled into a section of 20m of HNL-PCF (SC-5.0-1040) from *Crystal Fibre*, with a 3.2μm mode field diameter and a zero-dispersion wavelength of $\lambda_0=1040\text{nm}$. This generates a broad supercontinuum from 400nm to 1600nm. Then the HNL-PC was butt-coupled with the two-core PCF such that the light was launched into only one core. At the output port of the two-core fiber, the light from only one core was collected by an optical spectrum analyzer (OSA) by imaging the fiber endface with a microscope objective and blocking the light from the other core by a razor blade.

Since the beat length for the x-polarized and y-polarized modes are nearly identical for short wavelengths as shown in Fig. 5.8, the polarization effects in the experiment have been neglected. The experimental results for both structures at different fiber lengths are shown in Fig. 5.22 which is observed at the OSA as shown in Fig. 5.21. The transmission spectrum of either one of the cores shows almost periodic transmission, which reflects that for different wavelengths an identical fiber length leads to a different phase difference between the two supermodes. The smaller air-filling fractions and much closer core-to-core separation ($[d/\Lambda]_A=0.35$, $S_A=\sqrt{3}\Lambda$ and $[d/\Lambda]_B=0.56$, $S_B=3\Lambda$) resulted in a much shorter beat length for structure A as compared to that of structure B. This is reflected by the broader period of the spectrum in Fig. 5.22 (b) than that in Fig. 5.22 (a).

(a)

Figure 5.22: Transmission spectrum from one of the two cores for (a) structure A (b) structure B at different fiber lengths of the same fiber.

The spacing of the points of minimum transmission $\Delta\lambda$, depends on the wavelength, indicating the dependence of the beat length on wavelength. From the measurements in Fig. 5.22 (a), it is determined that by cutting back the two-core PCF structure A from 0.55m to 0.5m and then to 0.232m, the periodic wavelength spacing between two adjacent minima is increased from 4.7nm to 5.0nm and then to 8.1nm (near 940nm wavelength). This periodicity should change inversely proportional to the length of the fiber according to Eq. (5.15). This is confirmed by plotting the measured $\Delta\lambda/\lambda$ of structure A versus fiber length L as shown by the solid curve fitting line in Fig. 5.23, which shows an inverse proportional relationship with a chi-squared value $R=0.9968$.

Figure 5.23: $(\Delta\lambda/\lambda)$ as an inverse proportionality to fiber length.

From the transmissions in Fig. 5.22, we determine the beat lengths at different wavelengths according to Eq. (5.11) and Eq. (5.15). The experimental data points are plotted in Fig. 5.24. When an automatic power function fitting curve is used, the wavelength dependence of the beat length is found to be $L_c = 0.00384\lambda^{-1.276}$ for fiber A. The value of $\eta = 1.276$ is reasonably close to the calculated value of $\eta^x = 1.143$ and $\eta^y = 1.184$, but the uncertainty in η is quite large (44.3%) due to the large scatter in the experimental data points.

To show this, we also perform a curve fit to this data with the calculated theoretical value of the η coefficient from section 5.3.2. We use $\eta = 1.143$ and fit Eq (5.11) again with Q as the fit parameter. A new power function $L_c = 0.00393\lambda^{-1.143}$ is obtained with an acceptable chi-squared value ($R = 0.9177$). This fit curve is also shown in Fig. 5.24. The uncertainty in the η parameter would be reduced by increasing the

wavelength range over which the beat lengths were measured, but this remains limited by the useable transmission window of the polymer fiber (from 500nm to 900nm). The deviation between the simulation results ($Q=0.010$) and the experimental data ($Q=0.00393$) is attributed to the extreme dependence of the beat length on the structure asymmetry [154]. Moreover, the polarization effects are neglected without any polarization control.

Figure 5.24: Results of the beat length for PCF structure A: The dashed curves represented the fitting results with Q and η as free parameters, and the solid curves show the fit curves with only C as the fitting parameter.

When cutting back the two-core structure B from 0.895m to 0.685m, and then to 0.51m, the inverse proportional trend of wavelength spacing is not as obvious. The chi-squared value of the dotted fitting curve in Fig. 5.23 is 0.7193. We believe the reason for this is that for fiber B, the beat length is just under 10% of the fiber length (as opposed to about 1% for fiber A), and as a result, the fringes in the transmission

spectrum have quite large spacing. This results in a discrepancy from the prediction of Eq. (5.15), which relies on the assumption $\Delta\lambda / \lambda \ll 1$.

Figure 5.25: Results of the beat length for PCF structure B: The dashed curves represented the fitting results with Q and η as free parameters, and the solid curves show the fit curves with only Q as the fitting parameter.

The beat length variation with wavelength is shown by the points in Fig. 5.25. When an automatic power function fitting curve of the form of Eq (5.11) is used, the wavelength dependence of the beat length is found to be $L_c = 0.0352\lambda^{-0.581}$ for this fiber. This is in reasonable agreement with the calculated result of $\eta^x=0.622$ and $\eta^y=0.628$, for the wavelength dependence of the beat length of fiber B, though again, the uncertainty is large (65.3%) due to point scatter. Therefore we again use the calculated value of η in the fit procedure and find $L_c = 0.0346\lambda^{-0.622}$ with $R=0.827$. Again, the deviation between the simulation $Q=0.135$ and the experimental result

$Q=0.0346$ is attributed to the extreme dependence of the beat length on the structure asymmetry and the neglect of polarization effects. And as expected, the Q coefficient is much larger than was found for structure A ($Q=0.00393$) because the coupling is relatively weak in this case since the two cores are quite far away ($S=3\Lambda$), leading to a much larger beat length.

5.5 Conclusions

In conclusion, we have investigated two-core PCF structures both theoretically and experimentally. We have analyzed the coupled mode theory in two-core PCFs using a simple effective index model, which provides a straightforward illustration of the evolution trend of coupling coefficient with structure variations. Coupling coefficient increases with the increase of pitch size or decrease of air-hole size. And we found that the wavelength dependence of the coupling in PCF was smaller than that in conventional two-core structures, which shows two-core PCF is a more suitable candidate for broadband directional coupler. Super mode theory based on a planewave method is further demonstrated for a much accurate modeling of two-core PCFs. Much effort has been put into the real fabrications by using both silica and polymer materials. Structures with closely-adjacent and far-separated cores are successfully fabricated. Measurement of coupling coefficient is carried out, and the wavelength dependence can be obtained directly from the interference spectrum. The experimental results show an acceptable agreement with the theoretical calculations. Many useful devices can be constructed from these two-core fibers, such as optical switches, wavelength-selectors and two-core fiber amplifiers.

6

PCF based Long Period Grating

6.1 Introduction

The core-to-core coupling effects were analyzed in detail in Chapter 6, and it would be interesting to explore the core to cladding mode coupling in PCF. This chapter will demonstrate the characteristic of PCF based LPG. The fabrication, theoretical and experimental studies will be presented and discussed.

There are many possibilities of applying PCF into fiber optoelectronic devices, such as tunable PCF couplers [173] as we discussed in chapter 5, Bragg gratings using doped PCF [174] and long-period gratings (LPGs) [175], etc. These devices have shown the potential applications in WDM networks and sensing systems. Among these devices, LPGs have attracted the most attention because of the variety in fabrication techniques. Moreover, they have many advantages of low back-reflection and insertion loss, insensitive to electromagnetic interference, polarization independence and cost-effective. To distinguish the mechanisms of inscription of LPGs by different techniques, Malki *et al.* [176] studied the writing mechanism of electric-arc-induced LPGs in SMF-28 by Raman and luminescence spectroscopy, and

found that the local fiber structural re-arrangement and the weak geometrical deformation of glass modified the refractive indices of the core and cladding of optical fiber, whereas Kim *et al.* [177] proposed the effect of CO₂ laser irradiation on the refractive-index change in traditional fibers by measuring the interference fringe shift formed by a pair of LPGs. Although they depicted the mechanisms of the grating formation in normal fibers by the different techniques, much attention has recently been on the unique characterizations, which the LPGs in PCF possess. Humbert *et al.* [178] reported the characterization of LPGs in PCF at temperature from 20°C up to 1200°C, however, for the sensing technology, the property of gratings under applied strain should also be probed. Zhou *et al.* [179] recently performed tensile tests on PCF, and confirmed that they have a higher practical strength than traditional fiber. Morishita and Miyake [180] presented a writing technique, with which LPGs can be formed in the pure silica PCF by arc discharge without physical deformation. More recently, a more straightforward method to induce the gratings by microbending was reported in [181], each groove of the microbending will induce a local index change in the fiber via the photoelastic effect and such gratings can be completely erased by removing the pressure from the fiber. Because of the existence of microstructured air-holes, the effective index shows strong wavelength dependence, which will result some novel characteristics of this grating device.

In this chapter, these characteristics will be investigated in detail and the systematic comparison with the SMF based LPG will be presented. The endlessly single-mode PCF (ESM-PCF) is fabricated and supplied by the company *Crystal Fibre*. The fiber has a hole-pitch Λ of about 7.4 μm and air-hole diameter of 3.2 μm . The core diameter is defined by $d_{co} \approx 11.6\mu\text{m}$. The diameter of holey region is about 60 μm , and the

outside diameter of fiber is the typical value of 125 μm . These fibers are single-mode at all wavelengths for which fused silica is transparent.

6.2 Theoretical Study

Coupled mode theory is a method to analyze the light propagation in a perturbed or weakly coupled waveguides. The basic idea of the coupled mode theory is that the modes of the unperturbed or uncoupled structures are defined and solved first. Then a linear combination of these modes is used as a trial solution to Maxwell's equations for complicated perturbed or coupled structures. After that, the derived coupled mode equations can be solved analytically or by numerical methods. The theory assumes that the field of the coupled structures may be sufficiently represented by a linear superposition of the modes of the often accurate mathematical description of electromagnetic wave propagation. The coupled mode theory is widely used for the modeling of waveguide devices and most useful in the analysis of the interaction between several near resonance guided modes.

In LPGs, mode coupling occurs between a co-directional propagating core mode (LP_{01}) and i th cladding mode (LP_{1i}) where $i=2, 3, 4...$, when the phase-matching condition is satisfied [182]:

$$\Delta\beta = \beta_c - \beta_{cl}^i = 2\pi / \Lambda_G \quad (6.1)$$

where β_c and β_{cl}^i are the propagation constants of the core and i th cladding mode, respectively and Λ_G is the grating period. Then we can get the resonance wavelength accordingly:

$$\lambda_i = (n_c - n_{cl}^i) \Lambda_G \quad (6.2)$$

where n_c and n_{cl}^i are the effective index of the core mode and i th cladding mode. To understand the shift of resonance wavelength, we can expand Eq. (6.2) using a Taylor series:

$$\lambda = \lambda_i + \left. \frac{d\lambda}{d\Lambda_G} \right|_{\lambda_i} \Delta\Lambda_G + \frac{d^2\lambda}{d\Lambda_G^2} \Big|_{\lambda_i} \Delta\Lambda_G^2 + \dots \quad (6.3)$$

The higher order items can be ignored because of small $\Delta\Lambda_G$, and

$$\lambda = \lambda_i + \frac{d\lambda}{d\Lambda_G} \Delta\Lambda_G \quad (6.4)$$

In SMF based LPGs, the resonance dip will shift to the longer wavelength directly proportionally with the increase of the grating period because the $d\lambda/d\Lambda_G$ is a positive coefficient [183]. However, some special characteristics of PCF can be predicted due to the highly dispersive cladding modes that make the property distinguished from the LPG in the conventional SMF. To understand the property of PCF based LPG, we calculate the coupling wavelength λ_i of first three cladding modes $i=2, 3$ and 4 as shown in Fig. 6.1. The resonance wavelength is theoretically proven to decrease with the increase of grating period. Thus the $d\lambda/d\Lambda_G$ is a negative coefficient which results in a blue-shift of resonance wavelength with grating period according to Eq. (6.4). The trend is opposite compared with SMF based LPG. In Fig. 6.1, the coupling between the core and claddings for PCF with different air-hole size are illustrated: $d=5\mu\text{m}$, $4\mu\text{m}$, $3\mu\text{m}$ and the hole-to-hole pitch size is fixed at $8\mu\text{m}$. Different shaped lines are for different cladding modes. The larger the air-filling fraction, the smaller is the effective cladding index. Consequently, a smaller grating period should be applied for PCF with bigger air-hole diameter in order to achieve the same coupling wavelength.

Figure 6.1: (a) Fundamental mode. (b) First order cladding mode in a typical four-ring ESM-PCF. (c) Blue shift of resonance wavelength for the first three cladding modes with the increase of grating period for different air-hole size.

There are many factors that influence the depth of the attenuation bands of the LPGs: the cross coupling coefficient between the core mode and the cladding mode that couples at that resonance wavelength, the length of the grating. The relationship can be shown as [184]:

$$T_i = 1 - \sin^2(k_i L) \quad (6.5)$$

where k_i is the coupling coefficient of the i th cladding mode, L is the length of the grating and T_i is the minimum transmission of the attenuation band. The oscillation behavior for the transmission dips are shown in Fig. 6.2 versus different κL products.

Figure 6.2: Oscillation of transmission dips by varying the κL products.

By the couple-mode theory, the mode-coupling coefficient is a function of the index change and the modal overlap between the guided and cladding modes over the region of perturbation [185]:

$$\kappa_{c,cl} = \frac{\pi}{\lambda} \sqrt{\frac{\epsilon_0}{\mu_0}} n_0 \int_A E^c(x, y) \Delta n(x, y) \times E^{cl}(x, y) dx dy \quad (6.6)$$

where $E^c(x, y)$ and $E^{cl}(x, y)$ are the field distributions of the core and cladding modes, respectively; n_0 is the average refractive index of the fiber, and $\Delta n(x, y)$ is the induced perturbation profile.

6.3 Fabrication of PCF based LPG

6.3.1 Stress Relaxation Technique

It is well known that LPGs can be formed in germanium-doped silica fiber by the use of UV- light irradiation with hydrogenation and amplitude mask technique. However, the formation of LPGs is not straightforward in most PCFs with a pure-silica core because there is no photosensitivity provided by germanium-oxygen vacancy defect centers, which can be permanently photo-ionized by ultraviolet (UV) absorption to cause a refractive index change through the Kramers-Kronig relation [186]. It was described that the fabrication of LPGs in pure silica PCF were realized primarily by modification of glass structure as [187] previously demonstrated. In this section we present a LPG based on an ESM-PCF by using the focused pulses of CO₂ laser with periodic stress relaxation and point-by-point technique, the experimental setup is shown in Fig. 6.3. The whole fabrication system consists of CO₂ laser (Synrad series 48-1 with power output of 10W ± 10%), two fiber holders with translation stages, two charge coupled device (CCD) cameras each mounted on 45° angle to capture the fiber image, a broadband super luminescent diode (SLD), an OSA, and a computer. Two

SLDs were coupled to illuminate the fiber from 1260-1650nm while the output spectra were measured with an OSA.

Figure 6.3: Setup for fabrication of PCF based LPG using CO₂ laser.

During the PCF drawing process a melting preform is drawn to a size of normal fiber diameter (125 μ m). The tension is accumulated in fiber core, while the compression is generated in the cladding when the silica is frozen. The mechanically residual stress influences the refractive indices of core and cladding. Under the focused pulse of CO₂ laser, the refractive index can be modified as illustrated in Figure 6.4. It is worth noting that due to the mechanical tension embedded in core, the change in refractive index ($\sim 8.5 \times 10^{-4}$) [75] [188]-[189] is enough to inscribe the LPGs in PCF, which could be realized by periodical stress relaxation without holes collapse. We can easily achieve grating notch more than 30dB as shown in Fig. 6.5.

Figure 6.4: Refractive index change in PCF with mechanical stress relaxation.

Figure 6.5: Transmission spectra of resonance wavelengths of LPGs in ESM-PCF and SMF at room temperature, before and after 1 hour at 992 °C, respectively. Inset, optical micrograph of fiber appearance after the LPG inscription.

The characterization of formed LPGs at high temperature was performed with a tubular furnace, no external physical deformation observed after the ESM-PCF treated by the heat source of CO₂ laser. In thermal experiments, one grating in EMS-PCF (6 periods of $\Lambda_G=530\mu\text{m}$, $\lambda_i=1299.59\text{nm}$ of resonance wavelength with isolation loss of -28dB) and another grating in SMF (15 periods of $\Lambda_G=500\mu\text{m}$, $\lambda_i=1252.95\text{nm}$ with isolation loss of -22dB) were heated from room temperature 24°C to 992°C at an average rate of $10^\circ\text{C}/\text{min}$. The transmission spectra of gratings at room temperature and 992°C are shown in Fig. 6.5. For the shifts of resonance wavelength at different temperature, the grating based on ESM-PCF is much less sensitive than that in SMF, and this is because of unique material of PCF, and in turn no viscoelastic effect between the fiber core and cladding. The inset of Fig. 6.5 shows the optical micrograph of fiber appearance with LPG, and no external physical deformation was observed after the ESM-PCF treated by CO₂ laser. The coefficients of temperature sensitivity for LPG in ESM-PCF and SMF are measured to be $10.9\text{pm}/^\circ\text{C}$ and $119\text{pm}/^\circ\text{C}$, respectively. The resonance wavelengths shift with temperature toward longer wavelength region, as expected by phase-matching condition. It can be seen that there were many ripples on the transmission spectrum of curves b and c, which might be induced by the structural re-arrangement of silica and multiple mode-coupling at high temperature.

6.3.2 Photoelastic Technique

We have described the fabrication of PCF based LPG by using periodic stress relaxation of CO₂ laser and point-by-point technique in the previous section. However, this technique induces the periodic modulation of the fiber refractive index by

deforming the internal fiber structure permanently, and restricts the tunability of this grating device. A more straightforward method to induce the gratings by photoelastic effects will be presented in this section. The periodic local refractive index change is induced by the photoelastic effects from a periodic grooved fixture as shown in Fig. 6.6. Such gratings can be completely erased by removing the pressure from the fiber.

Figure 6.6: Left: the cross-sectional image of the PCF used in the experiment and the coordinate system for the fiber showing the applied external force F . Right: the grooved fixture with a period 500 μm.

A PCF based mechanical LPG (MLPG) was obtained by applying a transverse force on a section of PCF by a periodically grooved plate as shown in Fig. 6.6. The grooved fixtures were mechanically polished with rectangular grooves of period (Λ_G) around 500 μm. The length, width and thickness of the grooved plate were 50 mm, 20 mm, and 5 mm, respectively. The number of grooves on the plate is 100. The transverse force F was manually controlled by a stress gauge with a resolution of 0.1 N. The cross coupling strength can be simply varied by changing the transversal pressure. The surface of the grooved plates is flat rather than knife-edges, so the point of maximum stress moves a short distance away from the outer cladding surface. At the center of

fiber, the change of refractive index is $\delta n = \frac{4n_0}{\pi D} \cdot \frac{F}{\Lambda_G / 2} (q_{12} - q_{11}) \approx 0.014$ [190],

where $n_0=1.45$ is the refractive index of fused silica, D is the fiber diameter $125\mu\text{m}$, q_{11} and q_{12} are the piezo-optic coefficients. This applies for an optically isotropic material [190]. However, due to the microstructure of the cladding in PCF, the average change of cladding index will be much closer to the index change of the core. When the applied stress F was increased from 10N to 60N with a step of 10N, the core mode firstly experienced an increase of energy transferring to cladding mode, thus the amplitude of the transmission dip of MLPG became deeper. But when the transmission dip reaches the minimum, the cladding mode would couple back to the fundamental core mode, so the depth of the dip was reduced. The mode coupling between the core and cladding is oscillating as shown in Fig. 6.7 (a). This result agrees well with the theoretical simulations in Fig. 6.2. This oscillation also indicates that the cross coupling coefficient is direct-proportional to the applied transversal force as implied in Fig. 6.7 (b). The grating period in this case was not varied significantly with the increase of the applied force since the grooved plate was placed on top of a flat surface. Thus the shift of resonance wavelength was not significant.

Apart from the effect of applied stress, the grating length L_G will also cause the amplitude variation of transmission spectrum in PCF based MLPGs and theoretically the bandwidth of the spectrum will reduce with the increment of L_G . A section of PCF was tilted by an angle of $\theta = 21.8^\circ$ but put at different positions to achieve various grating length from 40mm to 48mm. The refractive index variation is the same since the applied stress F is fixed at 50N. When the grating length was increased from 44mm to 48mm, the bandwidth of the grating spectrum was reduced from 22.5nm to 16.5nm. The amplitude of transmission dip was oscillating from minimum to

maximum, and the results shown in Fig. 6.8 agreed well with Eq. (6.5). The slight variation of the resonance wavelength is due to the discrepancy in aligning the fiber at the same angle each time. The different alignment angle will cause different grating period, which will be reflected as the variation of the resonance wavelength.

(a)

(b)

Figure 6.7: (a) Transmission spectrum; (b) Transmission dips oscillation for PCF-based MLPGs under different stress force: $L_G=50\text{mm}$, $\Lambda_G=500\mu\text{m}$.

Figure 6.8: Transmission spectrum with different grating length PCF based MLPG.

BW is the FWHM bandwidth.

To investigate the temperature stability of this PCF based MLPG, the device was demonstrated on top of the flat surface of a thermal heater (CIMAREC2). The temperature was manually controlled from 30°C to 110°C with a step of 5°C. The shift of resonance wavelength for PCF based MLPG was tested by increasing and decreasing the temperature as shown in Fig. 6.9. The average thermal coefficient of this mechanical grating device was measured to be -25 ~ -37pm/°C.

Figure 6.9: Shift of resonance wavelength with temperature.

It is interesting to note that the tracking of the resonance wavelength shift in the MLPG with heating and cooling did not overlap completely, indicating that the structural rearrangement of the silica is not thermodynamically reversible. The effective refractive index of the cladding in the cooling path is larger than that in the heating path, which gives rise to more of a resonance wavelength shift during fiber heating. Similar phenomenon was observed in reference [191]. Another interesting point is that the resonance wavelength shift to shorter wavelength as opposite to the case in LPGs inscribed using high power CO₂ lasers. This is because the variation of effective index will not dominant the structural change in this case because the fiber is under the periodic stress of the fixture which is a metal plate. With the increase of the temperature, the grating period will increase due to the thermal expansion. Then the resonant wavelength will be shifted to shorter wavelength according to Eq. (6.1).

6.4 Applications of PCF based LPG

6.4.1 Mach-Zehnder Interferometer with LPG Pair

The single MLPG has a relatively broad 3dB bandwidth ($>20\text{nm}$) as shown in Fig. 6.7 and Fig. 6.8, which limits their applicability as a wavelength selective filter. To overcome this difficulty, one of the possible solutions is to cascade multiple LPGs, which is characterized by narrow bandwidth as illustrated in Fig. 6.10. We can easily induce two identical MLPGs on a piece of PCF by using two grooved fixtures as shown in Fig. 6.11. The core and cladding modes propagate simultaneously in the grating-free region between two MLPGs, and the two modes then interact in the second MLPG to form the periodic modulation fringes in output spectrum. And a Mach-Zehnder interferometer (MZI) is formed.

Figure 6.10: Spectrums with different number of cascaded LPGs.

Figure 6.11: Schematic illustration of a MZI using MLPG pair.

The interference fringes are obtained when the relative phase between the core mode and co-propagating cladding mode is an integral multiple of 2π . And the fringe spacing S_f can be described as [192]:

$$S_f = \frac{\lambda^2}{\Delta m_{in} d + \Delta m_{out} (L_s - L_G)} = \frac{\lambda^2 / \Delta m_{out}}{(\Delta m_{in} / \Delta m_{out} - 1) L_G + L_s} \quad (6.7)$$

where λ is the free space wavelength, L_s is the separation between the centers of two cascaded LPGs, Δm is the effective differential group index. Subscripts “in” and “out” mean the value within the grating region and the value out of the grating, respectively. As shown in Fig. 6.12, when we separate the grating pair by a distance of $L_s=9.5\text{cm}$, a fringes separation $S_f=9.6\text{nm}$ is obtained. The fringe separation is decreased to 8.2nm when we increase the grating separation to 11.5cm .

In previous work, the fringe separation was approximately calculated based on the assumption that the effective group index difference with and without grating are very close to each other:

$$S_f \approx \frac{\lambda^2}{\Delta m_{out} L_s} \quad (6.8)$$

Most reports used the Δn_{eff} instead of Δm for the calculation of fringe separations.

The effective index difference of PCF without any index perturbation was predicted as $\Delta n_{eff} = (n_{co}^{eff} - n_{cl}^{eff}) \approx 2.8 \times 10^{-3}$ by using the theoretical result mentioned in [181].

However, the second term of the group index difference is a strong function of wavelength, which can be very scalable in PCF:

$$\Delta m \equiv \Delta n_{eff} - \lambda \frac{d}{d\lambda} \Delta n_{eff} \quad (6.9)$$

Figure 6.12: Interference pattern of two identical PCF based LPGs with different grating separation: (top) $L_s=9.5\text{cm}$; (bottom) $L_s=11.5\text{cm}$.

The measured fringe data at different grating separation are plotted in Fig. 6.12 when we apply a transversal force of $F=100\text{N}$. A curve fitting is performed by fitting the parameters of $\lambda^2 / \Delta m_{out}$ and $(\Delta m_{in} / \Delta m_{out} - 1)L_G$ based on the following expression:

$$S_f = \frac{\lambda^2 / \Delta m_{out}}{(\Delta m_{in} / \Delta m_{out} - 1)L_G + L_s} \quad (6.10)$$

A theoretical fitting expression of $S_f = 171.4 / (8.749 + L_s)$ is obtained with Chi-square value of $R=0.9795$, which indicates a very good agreement between the theoretical and experimental results. From the theoretical fitting results in Fig. 6.13, we calculate effective group index without any index perturbation $\Delta m_{out}=1.18 \times 10^{-3}$, the index variation with the transverse stress $\Delta m_{in}=3.23 \times 10^{-3}$.

Figure 6.13: Fringe spacing of the all-PCF MZI measured as a function of grating separation. The fitting curve represents the best-fitting curve with respect to the grating separation.

6.4.2 Mach-Zehnder Interferometer with Single LPG

Recently, Dong *et al.* proposed a new design of a single LPG-based wavelength-selective all-fiber filter [193], in which a misalignment splicing point (MSP) is formed to interact with the single mode fiber based LPG. Similarly, the new structure can be deployed to form an all-PCF based MZI as shown in Fig. 6.14. The MSP formed by using a commercial fusion splicer under the manual mode functions as a light splitter which couples a part of the core mode power into the cladding modes so it may replace the first MLPG in an LPG pair to form a MZI. Due to the much easier formation of the MSP than LPG or metal-coating end mirror in optical fibers, this proposed PCF filter has a lower cost and reduced technical difficulty, while the flexibility, e.g., adjustment of the channel spacing is enhanced.

Figure 6.14: Schematic diagram of the single LPG-based MZI with the illustration of the interference between the core and cladding modes. The bottom left picture shows the fiber in the splicer screen forming the MSP.

Fig. 6.15 shows the measured transmission spectra of the MSP-LPG using PCF. The separation between the MSP and the center of the LPG is ~ 9 cm. It can be seen that up to ten equally spaced loss peaks appear in a wide bandwidth ~ 25 nm. Isolation of 8dB

was obtained around the center of the resonant wavelength band. The fringe spacing for the pass-channels was measured to be 2.5nm. The dependence of the fringe spacing on the MSP to LPG spacing can be expected to be similar to the case of MLPG pair. The insertion loss for the MSP-LPG based MZI is about 3dB higher compared with the insertion loss of the LPG pair in the previous section. This may be caused by radiation-mode coupling and the scattering loss at the MSP. Further optimization of the parameters for the MSP formation, such as the offset of the fiber cores and the splicing arc power and duration, may result in a smaller insertion loss. Much smaller fringe spacing can be achieved by increasing the separations between the grating the MSP. Compared with the conventional design in reference [193], some unique properties of PCF can be used to achieve special characteristics of such MZI.

Figure 6.15: The modulation fringes from the MSP-LPG based PCF MZI.

Firstly, we can take advantage of the existence of air-holes, and inject them with liquids so that this filter device can be used as sensor. Secondly, the MLPG is tunable which makes the shift of operating wavelength possible. This novel structure can be used as a wavelength selective all-PCF filter, which performed as a MZI with good isolation and low insertion loss. The simple design and easy fabrication make it highly cost-efficient among the several reported PCF based MZIs.

6.4.3 Torsion Sensitivity Measurement with LPG

In this part, we want to apply the PCF based MLPG introduced in section 6.2.2 into a twisted fiber system to investigate the torsion sensitivity. The relationship of the resonance wavelength shift with twisting angle is studied and compared with that of LPG inscribed in SMF. The primary advantage of MLPG is the tunability of several parameters: firstly, the grating period can be tuned by adjusting the angle (α) between the grooved plate and fiber longitudinal axis; secondly, the coupling coefficient κ , which determines the strength of mode coupling and is proportional to the index variation induced by photoelastic effects, is easily controlled by the pressure of the period grooved plate; and the transmission spectrum is reversible and removable with a good repeatability.

We firstly measured the optical activity coefficient g-value [37] for three types of fiber, SMF, ESM-PCF and polarization maintaining PCF (PM-PCF). The light launched from a tunable laser source at 1550nm followed by a polarizer goes into a section of twisted fiber. A polarimeter is used to obtain the S-parameters at different twisting angles. The input the state of polarization (SOP) is fixed at $[1 \ 0 \ 0]$. Thus the

g -values are calculated from the S-parameter according to $S_1 = \cos(g\theta)$ [194], where θ is the twisting angle, and g is a suitable physical constant representing the proportionality between the twist rate and the induced circular birefringence. The birefringence B is also listed in Table 6.1. Compared with the SMF that has an average birefringence value of 10^{-6} , the large index contrast and hexagonal-shaped core facilitate PCF around two orders greater.

Fiber-type	SMF	ESM-PCF	PM-PCF
$B (\lambda=1550\text{nm})$	10^{-6}	10^{-4}	8.6×10^{-4}
g	0.16	0.13	2.0

Table 6.1: List of birefringence and g -values for three types of fiber.

Figure 6.16: The experimental setup for measuring the torsion sensitivity of the PCF. Insets show the cross-sectional image of the PCF and the grooved fixture.

The ESM-PCF based MLPG and the experiment setup for demonstrating the shift of resonance wavelength by changing θ is shown in Fig. 6.16. It consists of a MLPG and a twist region which is composed of a fiber twister and a fiber holder with $L=16\text{cm}$. The PCF in the twist region is straightened in order to avoid bending effects. The

applied pressure is fixed at $P=6.174 \text{ kN/m}^2$. Higher linear-birefringence of the fiber under stress is achieved by increasing the transversal pressure. To test the resonance wavelength shift of the PCF based MLPG, a broadband 1260~1460nm SLD light source is used. The transmission spectrum was measured with an OSA. The polarizer is tuned to obtain an initial resonance at the longest wavelength, named $\lambda_{\max}$. As the twisting angle θ increases, the polarization angle Φ of the input light varies linearly accordingly as $\Phi=g\theta/2$ [194].

Due to the variations of polarization angle and the field components along the two orthogonal axes, the resonance wavelength will oscillate between $\lambda_{\max}$ and $\lambda_{\min}$ and the turning point is at $\theta \approx 7.7\pi$. The theory agrees well with the evolution of the resonance wavelength shift shown in Fig. 6.17 (a). The variation from curve-a to curve-d indicates the rotation of polarization angle from 0° to $\sim 70^\circ$, whereas the transition from curve-d towards the dashed and dotted curves shows the reverse trend of variation, representing the polarization angle is beyond 90° . The blue-shift of resonance wavelength is measured to be $0.73\text{nm}/2\pi$ for both transmission dips near 1393nm and 1403nm.

In purpose of a better understanding about the torsion sensitivity of PCF based MLPGs, a comparison with SMF based MLPGs is demonstrated in Fig. 6.17 (b). The resonance wavelength for the mode coupling near 1495nm is blue-shifted, which follows the same trend of variation as PCF when the torsion rate increases ($0 < \Phi < 90^\circ$). But the red-shift of resonance wavelength happens near 1387nm. The resonance wavelength shift with the twisting angle is $0.33\text{nm}/2\pi$, where the sensitivity is reduced by half compared with PCF. Moreover, many ripples were observed in the spectrum, introducing inaccuracy factors to the system.

(a)

(b)

Figure 6.17: (a) Transmission spectrum of PCF based MLPG by increasing the twisting angle θ . The inset shows the torsion sensitivity. (b) Transmission spectrum of SMF based MLPGs.

The g parameter is almost identical for SMF and PCF, which means that the circular birefringence induced by a fixed twist rate is almost the same. So we can conclude the

torsion sensitivity difference is due to the grating devices only. Which means that PCF and SMF based LPGs have different polarization state responsibilities. It can be qualitatively explained by the highly dispersive cladding structure in PCF, $(n_c - n'_{cl})$ is a strong function on wavelength. But the standard SMF cladding is non-dispersive, the dependence of $(n_c - n'_{cl})$ on wavelength is not as strong as that in PCF.

6.5 Conclusions

We have discussed about an important application of PCF in this chapter. PCF based LPGs have been fabricated by both stress relaxation technique using CO₂ laser as well as photoelastic technique using periodic microbending grooves. We have theoretically analyzed the novel properties of PCF based LPGs, such as the blue-shift properties of the resonance wavelength. Experimental investigation and characterization has also been carried out for the LPGs properties at conditions of high temperature from 24 to 992°C. Compared with the temperature sensitivity of LPG in SMF, which is 119pm/°C, the CO₂ induced grating in ESM-PCF is more stable at high temperature (10.9pm/°C). And similarly thermal stability was demonstrated with photoelastic effects to achieve temperature sensitivity ~24pm/°C. The thermal stability makes PCF a potential candidate for the applications in harsh environments, such as space-aircraft, and nuclear-power plant. A *g*-value of 0.13 for an ESM-PCF has been measured directly from the output SOP. The torsion sensitivity has been experimentally characterized and the shift of resonance wavelength with the twisting angle is 0.73nm/2 π , which is two times larger than a similar grating using SMF. This coefficient can be further enhanced when improving its linear birefringence by using a larger mechanical pressure.

7 Conclusions and Future Work

7.1 Conclusions

It is meaningful and challenging to design PCF based components and to investigate their applications for optical communication system. In this thesis, we began with the historical and background overview of PCF technology, which motivated the study of this work. The overview highlighted the rapid development of this research domain mainly in the past decade. Then most of the applications were illustrated with the corresponding key experimental milestones.

Both vector form and scalar form wave equations were derived from the basic Maxwell's equations. Various numerical methods for the modeling were listed out and discussed. Beam propagation method (BPM) and plane wave method (PWM) have been discussed in detail. After considering the numerical accuracy and computational efficiency, these two methods were chosen for modeling the designs in this thesis. BPM is capable to handle loss problems, and PWM is a unique method to obtain the photonic bandgaps of any periodic structures.

The birefringence and dispersion characteristics were studied theoretically, and new designs of highly-birefringent (HiBi) PCF and dispersion-compensating (DC) PCF were proposed. Both index-guiding and bandgap-guiding structures with elliptical lattices were designed to obtain HiBi structures. Then we deployed a section of single material HiBi-PCF into a fiber laser system and effectively improved the temperature stability. Apart from the birefringence, the dispersion could also be tailored in PCFs. Structure with two concentric-cores was proposed for achieving large dispersion value at 1550nm wavelength. Negative dispersion up to -6000ps/km-nm was obtained. Such fiber components can effectively engineer the dispersion in a transmission system. The idea of an abrupt coupling between two concentric-cores was further extended to a microstructure with elliptical air-holes so that the dispersion compensation could be realized even in a polarization maintaining system.

An intensive theoretical analysis and experimental investigations have been carried out to investigate the coupling effects in two-core PCFs. The derivations and constraints of coupled mode theory and super mode theory in PCFs were theoretically analyzed. The fabrication process of silica and polymer two-core PCFs were both demonstrated. We experimentally measured the coupling coefficient and its wavelength dependence, and it agreed well with the numerical results.

Finally, we have experimentally demonstrated the properties of PCF based LPGs, including anomalous mode coupling and temperature insensitivity. Both stress relaxation method using CO₂ laser and photoelastic effect based microbending were utilized to fabricate PCF based LPGs. They were compared with SMF based LPGs theoretically and experimentally. We further investigated applications of LPG based

device, such as a wavelength filter based on Mach Zehnder interferometers and the measurement of torsion sensitivity.

As PCFs are attracting more attention and they are revolutionizing the physics of optical waveguides, we can expect these microstructured novel fibers will lead to more possibilities for optical communication.

7.2 Recommendations for Future Work

Although an intensive investigation of novel designs of PCFs and PCF based devices has been presented in this thesis, there still exist several research topics worth to be carried out for future work.

One common issue that is valuable to be extended as the future work is the implementations of PCF fabrication. In particular, those novel designs proposed in chapter 3 and chapter 4 are worth to be realized in experiment, especially the dispersion compensating PCFs. In order to accomplish the dispersion compensation for a wider wavelength range, some further optimization to the structure can be carried out systematically. Currently, these complicated structures have not been fabricated due to the technical constraints. These structures require a precise control of different air-hole sizes, especially when it is a concentric-core design. However, from the same set of capillaries and tubes and same drawing parameters, we are not able to get identical fibers each time.

Another recommendation is to investigate the polarization properties of PCF, for both index-guiding and bandgap-guiding structures. With the study of group theories and exploration of symmetry property in a microstructure, the polarization effects and polarization dependent loss can be analyzed, measured and controlled. Actually, there has been some interesting work to apply polarization-maintaining fiber (PMF) based long period grating (LPG) as a polarizer. The double resonance was utilized for the controlling of polarization [195, 196]. However, the LPGs used in these work were all fabricated by the UV-light, which limited the device tunability. The fabrication of LPG in a PMF can be further extended to PM-PCF. From chapter 6 of our thesis, we understand that the resonance of PCF based mechanical LPG is tunable by applying different transversal pressures. Therefore, a tunable polarizer using PM-PCF can be demonstrated. This device is expected to offer much better temperature and strain stability. The most challenging part in such demonstration will be aligning the fast and slow axes properly to obtain the effectively separated resonances from the output spectrum.

Apart from the fused silica PCFs, actively doped structures are also worth to explore, especially their applications in fiber laser systems. For example, the combination of novel PCF design with Yb-doped core result in unique properties for high power lasers. Some preliminary work was shown in [197, 198]. The double-cladding concept was extended to PCFs, with a promising feature of a high numerical aperture of the inner cladding. This is achieved by surrounding the inner cladding with a web of silica bridges which are substantially narrower than the wavelength of the guided radiation as shown in Fig. 7.1 (a). With the doping in the core, the effective mode index is slight increased with a well-confined triangular shape mode distribution shown in Fig.

7.1 (b). Theoretical studies have led to the conclusion that such air-clad Yb-doped large-mode-area PCF should be scalable to kW-level output powers. Thus it will be challenging to design PCF structures for high power laser application. The dispersion tailoring and nonlinearity tailoring are two crucial design perspectives. Meanwhile, it is interesting to deploy PM-PCF for high power delivery applications, since a stable degree of polarization is important for most laser sources.

Figure 7.1: (a) SEM image (b) intensity distribution of air-clad Ytterbium-doped PCF.

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1. “Photonic crystal fibers”, Yangtze Optical Fiber and Cables, China, Sep. 2004.
2. “Photonic crystal fibers”, Huazhong University of Science and Technology, China, Sep. 2004.
3. “Design and applications of photonic crystal fibers”, Chinese University of Hong Kong, China, Nov. 2004.
4. “Design and applications of photonic crystal fibers”, South China University of Science and Technology, China, Dec. 2004.
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