Investigation of magneto-optical properties of magnetic fluid for fiber optics applications

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Investigation of Magneto-Optical Properties of Magnetic Fluid for Fiber Optics Applications

Zu Peng

School of Chemical & Biomedical Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of

Doctor of Philosophy

2013

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research done by me and has not been submitted for a higher degree to any other University or Institute.

11/10/2013
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Date

Zu Peng
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Zu Peng

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Abstract

Magnetic fluid (MF) is a novel kind of magneto-optical functional material that possesses diverse magneto-optical properties such as tunable refractive index, birefringence effect, dichroism effect, Faraday effect, field dependent transmission property and so on. It can serve as the magnetically sensitive material playing the key role in magnetic field sensors and magneto-optical devices. There were many reported photonic devices based on MF in the literatures. This thesis focuses on investigating the magneto-optical properties of MF for fiber optics applications.

The thesis first reviewed the background knowledge including the MF, optical fibers and optical fiber interferometry. The physical origin of refractive index tunability and birefringence effect of MF are detailedly discussed in preparation for the works in the following Chapters.

In the thesis, we have presented three kinds of MF-based magnetic field sensors. The first one is based on the birefringence effect of MF. The MF is inserted into an optical fiber Loya-Sagnac interferometric configuration in the form of MF film. The sensitivity characteristics of this optical fiber Loya-Sagnac interferometric configuration are theoretically analyzed and experimentally verified. Finally, a sensitivity of 59.2 pm/Oe is achieved by applying the conclusions drawn from the theoretical analysis to the proposed magnetic field sensing configuration. The second one is based on refractive index tunability of MF and the evanescent field of photonic crystal fiber with air-holes collapse. The evanescent light field interacts with the MF and translates the magnetic field strengths into optical signals. A Mach-Zehnder interferometric configuration formed by cascading two sections of

photonic crystal fibers with air-holes collapse is used to demodulate the optical signals. The achieved sensitivity is 2.367 pm/Oe. The third one is based on the refractive index tunability of MF and the photonic bandgap effect of photonic crystal fiber. MF with higher refractive index value (>1.45) is filled into a photonic crystal fiber to convert an index guiding fiber into a photonic bandgap fiber. The photonic bandgap effect is dependent on the refractive index of the MF filled in, which can be tuned by external magnetic field. The achieved sensitivity of this sensor is 1.56 nm/Oe. The sensitivities of these three sensors are better than the reported results in the literatures. Especially, the achieved sensitivity of the third one is enhanced by 2-3 orders of magnitude.

In addition to the magnetic field sensors, two magneto-optical modulators are also developed. The first magneto-optical modulator is based on the optical fiber Løyt-Sagnac interferometric configuration. The achieved extinction ratio is improved to 19.5 dB. The second magneto-optical modulator is on the basis of polarimetric configuration, which is similar to previous one. Through some modifications, the extinction ratio of this modulator is improved to 38 dB. Both results of these two magneto-optical modulators are much better than the results in the literatures.

Taking advantage of the high-birefringence-fiber assisted polarimetric configuration, a physical phenomenon of MF, saying the laser self-induced tunable birefringence effect is also observed in the experiment. This phenomenon exists in both the zero field birefringence effect and magnetic field induced birefringence effect. The laser self-induced tunable birefringence effect follows a linear function whilst the field induced birefringence follows a Langevin function. This

polarimetric configuration can be used as a tool to observe other physical phenomena of the MF.

List of Abbreviations

ASE	Amplified Spontaneous Emission
CCW	Counterclockwise
CW	Clockwise
ER	Extinction Ratio
FBG	Fiber Bragg Grating
FLM	Fiber Loop Mirror
FPI	Fabry-Perot interferometer
FSR	Free Spectral Range
HBF	High Birefringence Fiber
LBF	Low Birefringence Fiber
LPG	Long Period Grating
MZI	Mach-Zehnder Interferometer
MF	Magnetic Fluid
MRI	Magnetic Resonance Imaging
OFSI	Optical Fiber Sagnac Interferometer
OPD	Optical Path Difference
OSA	Optical Spectrum Analyzer
PBG	Photonic Bandgap
PC	Polarization Controller
PCF	Photonic Crystal fiber
PD	Photodetector
PER	Polarization Extinction Ratio

List of Abbreviations

PMF	Polarization Maintaining Fiber
SEM	Scanning Electron Graph
SMF	Single Mode Fiber
SI	Sagnac Interferometer
TIR	Total Internal Reflection
TLS	Tunable Laser Source

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Chapter 1 Introduction

1.1 Motivation & Objectives

Magnetic field is almost everywhere and very important to the creatures on earth. For example, our earth is protected by its magnetic field from the solar wind or special energetic charged particles; Migrating birds rely on the magnetic field to navigate; Human organs like heart and brain also generate magnetic field. Many magnetic field devices have been developed and used in daily life. For example, magnetic resonance imaging (MRI) technology is used by doctors for detecting the inner structure of body; Electrical induction phenomenon is used to generate electrical powers; Various magnetic field sensors are used in daily life such as navigation, automotive applications, target detection, space research, geomagnetic measurements, electric current sensing and so on [1, 2]. Usually, the magnetic field is detected by electrical devices. However, the electrical devices cannot work properly in some harsh environment such as high voltage, extreme temperatures and high electromagnetic influence [3]. Optical fiber magnetic field sensors can work in these harsh environments due to their significant advantages such as immunity to electromagnetic interference, smart structure, low weight and noncontact measurement. In addition, optical fiber magnetic field sensors are characterized for their high measurement resolution, ultimate precision and capability of distributed sensing.

The key components of the optical fiber magnetic field sensors are the magnetically sensitive materials, which are responsible for interacting with the

magnetic field and converting the magnetic field signals into optical parameters. Magnetic fluid is such a novel kind of magnetically sensitive material that possesses diverse magneto-optical properties such as tunable refractive index, birefringence effect, dichroism effect, Faraday effect, field dependent transmission property and so on. Magnetic fluid is also a superparamagnetic material, which is very important to magnetic field sensing. There were some free space magneto-optical sensors based on magnetic fluid in the literatures, but only a few optical fiber magnetic field sensors based on magnetic fluid were reported. Yet, the great potentials of MF-based magnetic field sensors have not been fully explored.

On the other hand, with the great development in optical fiber technology in the past two decades, the performance of optical fiber sensors is also greatly improved. Especially, benefited from the great achievement in optical fiber communication, various kinds of optical fibers as well as a complete series of optical fiber components have been developed. Recently, the emergence of a new type of microstructured fiber, saying photonic crystal fiber, makes the optical fiber sensors more versatile and designable [4]. Various new photonic crystal fibers with special properties have been commercial available. Many research achievements of optical fiber sensors employed various photonic crystal fibers are intensively reported [5, 6].

The objectives of this thesis are to develop magnetic field sensors, especially all optical fiber magnetic field sensors, by combining the unique magneto-optical properties of magnetic fluid and the advantages of fiber optics technology. The efforts are devoted to improve the sensitivity of the magnetic field sensors based on magnetic fluid. Meanwhile, the proposed sensing configurations can be used to

observe the physical phenomenon of magnetic fluid and investigate the magneto-optical properties of magnetic fluid. The objectives of this thesis also include the development of the magneto-optical devices (e.g. magneto-optical modulators) on the basis of proposed sensing configurations. The efforts are also devoted to improve the extinction ratios of the magneto-optical modulators based on magnetic fluid.

1.2 Thesis Organization

The organization of the thesis is listed as follows:

- In Chapter 2, the background knowledge of this thesis has been reviewed including the properties of MF, the optical fibers and the optical fiber interferometry. We have focused on the magneto-optical properties of MF and reviewed their applications in fiber optics.
- In Chapter 3, the principle of optical fiber Sagnac interferometric configuration is discussed. A transverse force sensor is developed to understand how the linear birefringence works in the optical fiber Sagnac interferometric configuration whilst a twist sensor is developed to understand how the circular birefringence works in the optical fiber Sagnac interferometric configuration.
- In Chapter 4, we have developed magnetic field sensors and magneto-optical modulators based on the linear birefringence effect of MF. We first utilize the MF film in the optical fiber Sagnac interferometric configuration to realize a magnetic field sensor. Then a magneto-optical modulator is developed based on this optical fiber Sagnac interferometric configuration.

After that, a magneto-optical modulator based on polarimetric configuration is demonstrated to achieve an improved extinction ratio. Then, the sensitivity characteristics of optical fiber Sagnac interferometric configuration are theoretically analyzed and experimentally verified. According to the conclusions drawn from the theoretical analysis, a magnetic field sensor based on optical fiber Sagnac interferometric configuration has been experimentally demonstrated and its sensitivity has been enhanced. Finally, a phenomenon of laser self-induced tunable birefringence effect of MF is presented.

- In Chapter 5, two kinds of magnetic field sensors based on the tunable refractive index effect of MF have been developed. One magnetic field sensor is based on the evanescent field of photonic crystal fiber with air-holes collapse and optical fiber Mach-Zehnder interferometer. The other one is based on the tunable photonic bandgap effect of liquid filled photonic crystal fiber.
- In the last Chapter, Chapter 6, all the findings are summarised and some suggestions for the future research works are made.

Chapter 2 Literature Review

2.1 Magnetic Fluid

2.1.1 Introduction of Magnetic Fluid

Magnetic fluid (MF), also known as ferrofluid, is a highly stable colloidal suspension of nanoscale particles of magnetite, hematite or some other kinds of compound containing iron with the assistance of a suitable surfactant in suitable liquid carriers [7, 8]. The MF was first proposed and described in early 20th century, however until 1960s the stable MF was manufactured which led to intense research interests from researchers and engineers [7, 9]. Thereafter, as the quick development in the preparation, the fundamental physical mechanism and engineering, MF found a variety of applications. It was first used in the aerospace industry by NASA and then gradually came into the area of civil industries. Today many tons of MF-based devices are produced every year.

The MF is fabricated by chemical coprecipitation method. In the MF, the magnetic nanoparticles, for example Fe_3O_4 or Fe_2O_3 , are coated with long chained organic molecules as surface surfactants to prevent the magnetic particles from agglomerating due to van der Waals interaction [8]. The liquid carriers could be organic solvents like heptanes, xylene, toluene, kerosene, etc or could also be inorganic solvent water. The liquid carrier is the most dominant constituent which governs the overall physical properties of MF such as viscosity, refractive index, thermal stabilities and so on. In practice, water-based MF is the most commonly used. The magnetic particles' diameters are so small (10nm or less) that thermal

agitation or Brownian motion can disperse the magnetic particles uniformly in the liquid carriers. The surfactants are very efficient and the MF is stable, which means the magnetic nanoparticles do not agglomerate even in extremely strong magnetic field. Under externally applied magnetic field, the magnetic nanoparticles respond to the magnetic field and exhibit various unique properties including magnetic, optical, fluid dynamic and acoustic properties [8]. For example, as for the magnetic properties, MF exhibits different apparent densities under different magnetic field strength [10]; as for the optical properties, MF possesses tunable refractive index [11, 12], linear birefringence effect [13, 14], linear dichroism effect [15, 16], Faraday effect [17, 18], field dependent transmission effect [19, 20], magneto-chromatic effect [21, 22], thermal lens effect [23, 24] and so on; as for the fluid dynamic property, MF has different viscosities under alternating magnetic field [25, 26]; as for the acoustic properties, the acoustic waves travel in the MF with different speeds and experience different attenuations under different external magnetic field strengths [27, 28]. Especially, MF exhibits both the strong magnetism like solid magnetic material and the fluidity like liquid material. Besides, MF is a superparamagnetic material.

Since MF has so many unique properties, it has found a lot of applications in different areas. For example, one of the most widely used applications nowadays is the MF seal or ferrofluidic seal [29-31]. In the rotatory shaft sealing system, the MF is positioned between the shaft and stationary components to provide a hermetic seal while the shaft can rotate with very low friction or virtually no friction. The MF can be kept suspended in place simply by a strong enough magnetic field generated by a permanent magnet. Similarly, this friction-reducing capability of MF can be

employed to provide smooth surface by means of a strong enough magnet in other system.

Another typical wide use of MF nowadays is the cooling of loudspeaker [32]. The MF is positioned in the air space between the sound coil and the strong magnet, while the MF is kept in place by this magnet. Because the MF is superparamagnetic, it obeys the Curie's law, which means the MF has a weaker magnetization at a higher temperature but a stronger magnetization at a lower temperature. In other words, in the gradient temperature field where the voice coil produces heat and the magnet is colder, the magnet will attract cold MF more than the heat MF, so the MF plays a role to transfer heat from the hot voice coil toward the cold magnet (heat sink). This form of heat transfer is often referred to as thermomagnetic convection. This heat transfer method requires no additional energy input.

The MF can also be used as inertial sensors [33-36] including acceleration sensors or inclination sensors [37-40], tilt sensors [32, 38, 41-43] and so on. Figure 2-1 shows schematic diagram of an acceleration sensor based on magnetic fluid. A small magnet is levitated in the MF which is contained in a tube, whose position can be detected by the inductive coils surrounding the tube. Figure 2-2 shows a tilt sensor based on the use of MF. The partly filled MF acts as the core of inductors. The two coils are connected into a balance bridge circuit. When the sensor is placed horizontally, the volume of MF is equally divided within the two coils, so the inductance values of the two parts of MF are equal and the output signal is zero. When the sensor is tilted, some volume moves from one part to the other part, so the inductance values are not balanced and the output signal depends on the tilt angle.

Figure 2-1 Acceleration sensor based on magnetic fluid

Figure 2-2 Tilt sensor based on magnetic fluid

The MF also finds some applications in biomedical area [44-49]. In biomedical applications, the magnetic nanoparticles in MF can be used directly or acts as a part of polymeric supports. These supports can be attracted to the magnetic field, which enable them separated from liquid mixtures by means of the external magnetic field. The biologically active species, for example viruses, bacteria, and various cells, are absorbed on the surface of the polymeric supports which depends on their natures. Therefore the biologically active species can be selectively

separated. Besides, MF is also used as the contrast agents in the technology of for magnetic resonance imaging (MRI), which is often used cancer detection [48, 49].

There are also some other applications of MF such as adaptive mirrors [50-52], dampers [53-55], even in art and display and so on. In this thesis, we focus on the magneto-optical properties of MF and their applications. In the following Sections, these magneto-optical properties of MF will be introduced.

2.1.2 Refractive Index Tunability of Magnetic Fluid¹

The refractive index of MF is tunable by the change of the external applied magnetic field. This property is referred to as the refractive index tunability of MF [11, 12, 56]. The research group of Horng, Yang and Hong did a lot of investigations on the tunable refractive index property of MF including the origin, design, applications and so on. The refractive index tunability is one of the most often used magneto-optical properties of MF [57].

As discussed in the last Section, MF is a special polymer colloidal suspension with high stability. The ultra-fine ferromagnetic nanoparticles (e.g. Fe_3O_4) are dispersed uniformly in the liquid carrier with the assistance of the surface surfactants and Brownian motion [11]. The refractive index of the magnetic fluid under zero magnetic field increases on the basis of the intrinsic refractive index of the carrier after dispersing the ferromagnetic nanoparticles into the liquid

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carrier, which depends on the concentration of the nanoparticles [11]. The magnetic nanoparticles in the MF change from the random homogenous state to the field dependent structural pattern state when an external magnetic field is applied to the MF. The nanoparticles in the MF agglomerate and further form chains as well as magnetic columns along the direction of magnetic field. During the process of the formation of the magnetic columns, phase separation occurs between the columns and liquid in the magnetic fluid under the external magnetic field, which causes the variation of the effective dielectric constant of the magnetic fluid and, meanwhile, causes the variation of the effective refractive index of the magnetic fluid. The effective dielectric constant of the magnetic fluid is given as [56]:

$$\varepsilon_{MF} = \frac{-\varepsilon_c(1-f) - \varepsilon_l(f-1) + \sqrt{[\varepsilon_c(1-f) + \varepsilon_l(f-1)]^2 + 4(1+f)^2 \varepsilon_c \varepsilon_l}}{2(1+f)} \quad (2-1)$$

where ε_c and ε_l are the dielectric constants of the magnetic columns and the liquid phase, respectively. ε_l varies with the external magnetic field strength, but ε_c remains a constant. $f = (A_c/A)/(1 - A_c/A)$, where A_c/A describes the area ratio occupied by the magnetic columns, which is dependent on the external magnetic field strength.

$$\varepsilon_l |_{M_s, eff(H)} = n_{MF}^2 (M_s |_{H=0}) = (0.1573M_s + 1.3283)^2 \quad (2-2)$$

where M_s is the effective concentration of MF; $M_{s, eff(H)}$ is the effective contraction of MF under a magnetic field strength of H ; The effective dielectric constant ε_l of the liquid phase can be calculated by experiment. Therefore, Eq.(2-1) shows the effective dielectric constant ε_{MF} is a function of magnetic field strength.

Considering $n_{MF} = \sqrt{\epsilon_{MF}}$, the effective refractive index of the magnetic fluid is a function of the magnetic field strength.

The designing of refractive index of the MF is very important to the MF-based photonic devices. For example, the tunable filter based on the long period grating (LPG) requires the refractive index of MF which is lower than the refractive index of the fiber material, pure silica ($n_s=1.45$) [58, 59]; the magnetic field sensor based on the tunable photonic bandgap (PBG) effect of the photonic crystal fiber (PCF) requires that the refractive index which is higher than the refractive index of the fiber material [60]; the modulator based on MF requires the refractive index which is close but a little lower than the refractive index of MF [61]. Here, the factors that influence the refractive index of MF will be discussed.

The thermal energy of the nanoparticles and the magnetic energy of the nanoparticles are the two major factors that influence the refractive index of MF. The refractive index of MF under external magnetic field is dependent on the state of balance of the thermal energy and magnetic energy of the nanoparticles. The refractive index of MF $n_{MF}(H, T)$ can be given by [12]

$$n_{MF}(H, T) = (n_s - n_o) \left[\coth\left(\alpha \frac{H - H_{c,n}}{T}\right) - \frac{T}{\alpha(H - H_{c,n})} \right] + n_o \quad (2-3)$$

where α is a fitting coefficient. The MF has a threshold field strength which is named as critical field strength $H_{c,n}$. If the external magnetic field strength is smaller than this critical field strength (i.e. $H < H_{c,n}$), the refractive index of MF remains unchanged with the external magnetic field strength. If the external magnetic field strength is larger than this critical field strength (i.e. $H > H_{c,n}$), the refractive index of MF starts to increase with the external magnetic field strength. It

can be directly understood that, when the external magnetic field strength is smaller than the critical field strength, the thermal energy of the nanoparticles is dominant in the state of balance and the magnetic energy of the nanoparticles is not large enough to change the state of balance. $H_{c,n}$ depends on the environmental temperature T . The higher the environmental temperature, the larger the critical field strength. It can be easily understood that, higher temperature results in larger thermal energy of nanoparticles, which in turn requires more magnetic energy to start changing the state of balance.

In Eq.(2-3), n_o is the initial refractive index of MF, which is the refractive-index value when the external magnetic field strength is smaller than the critical field strength (i.e. $H < H_{c,n}$). n_o depends on the intrinsic refractive index of the liquid carrier and nanoparticle concentration of MF. The liquid carriers exhibit their own intrinsic refractive indices. For example, the intrinsic refractive indices of water, heptane and kerosene are about 1.33, 1.38 and 1.39, respectively. After the magnetic nanoparticles dispersed into the liquid carriers, the refractive index of the MF increases from the intrinsic refractive index corresponding to the liquid carrier linearly and continuously with the nanoparticle concentration [12]. Therefore, a MF with a higher initial refractive index (n_o) can be obtained either by using liquid carrier with higher refractive index or by using a MF with higher particle concentration.

As shown by Eq.(2-3), the MF exhibits a tunable refractive index by means of external magnetic field. The refractive index of MF increases with the external magnetic field strength, whose relationship follows a Langevin function [12]. When the magnetic field strength is small, the refractive index increase quickly and

linearly with the external magnetic field; then the variation of the refractive index increases slowly with the further increase of the external magnetic field; when the magnetic field strength is increased to be larger than a certain value, the variation of the refractive index tends to saturate. n_s is the saturated value of the refractive index of MF. The total variation range of the refractive index of MF under external magnetic field ($n_s - n_o$) is small whose typical value is about 0.003, and it depends on the nanoparticle concentration of the MF. As an example given by Ref.[12], for the MFs with different concentrations under external magnetic field, the variation trends of the refractive indices are similar, but the variation ranges of the refractive indices ($n_s - n_o$) are different. The larger the nanoparticle concentration of the MF, the larger the variation range of the refractive index. However, the nanoparticle concentration of MF is also subjected to the limit of saturation.

As shown by Eq.(2-3), the refractive index of MF is also dependent on the environmental temperature. Ref. [12] shows that the higher the environmental temperature, the smaller the total variation range ($n_s - n_o$) of the refractive index of MF with the external magnetic field strength. This phenomenon can also be explained by the state of balance between the thermal energy and magnetic energy. When the nanoparticles gain more thermal energy amidst higher environmental temperature but under the same strength of external magnetic field, the extra thermal energy gained will wash out certain magnetic field energy, which in turn suppress the change of the refractive index of MF.

The refractive index of MF also depends on the types of the magnetic nanoparticles. As an example given by Ref. [11], comparing the Fe_3O_4 -based MF

and the MnFe_2O_4 -based MF, the variation range of the refractive index under external magnetic field of the latter one is about 6 times as the former one.

The refractive index of MF also depends on the thickness of MF film. It is shown in Ref.[12] that, the thicker the MF film, the larger the variation range of the refractive index of MF under external magnetic field.

In the practical applications, for example, in order to achieve a better sensitivity for the magnetic field sensor based on the tunable refractive index of MF, it is often required a broader variation range of refractive index.

2.1.3 Linear Birefringence and Linear Dichroism of Magnetic

Fluid²

Linear birefringence is a kind of optical phenomenon that exists in anisotropic optical materials (Figure 2-3). Light propagating in this anisotropic material will decompose into two orthogonally linearly polarized light beams which propagate at different speeds, so it is called linear birefringence. One light beam propagates at the same speed no matter what its propagation direction is and it is defined as ordinary light or o-ray. The other light beam propagates at different speeds along different directions and it is defined as extraordinary light or e-ray. In other words, the anisotropic material exhibits different refractive index along different directions. In some directions, the e-ray and the o-ray propagate in the same direction and do not separate (but their speeds may or may not be the same) and these directions are defined as the optical axes or principal axes. There are 3 principal refractive indices

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in the optical crystal which are n_1 , n_2 and n_3 , respectively. If $n_1 = n_2 = n_3$, it is an isotropic material or homogenous material and there is no birefringence phenomenon. If $n_1 = n_2 \neq n_3$, it is uniaxial crystal. Usually, n_1 , n_2 are denoted by n_o whilst n_3 is denoted by n_e . The uniaxial crystal is further divided into positive uniaxial crystal ($n_e > n_o$) and negative uniaxial crystal ($n_e < n_o$). If $n_1 \neq n_2 \neq n_3$, it is a biaxial crystal.

Figure 2-3 Birefringence phenomenon of an optical crystal

In the uniaxial crystal, the refractive index along arbitrary direction can be given by

$$n(\theta) = \frac{n_o n_e}{\sqrt{n_o^2 \sin^2 \theta + n_e^2 \cos^2 \theta}} \quad (2-4)$$

where θ is the angle between the polarization direction of the light and the direction of the principal axis. The linear birefringence B is defined as $B = n_e - n_o$.

Since the e-ray and o-ray propagate at different speeds, a phase difference is

introduced between them. If the incident light is perpendicular to the principal axis of the uniaxial crystal, the phase difference can be given by

$$\varphi = \frac{2\pi}{\lambda} |n_e - n_o| d \quad (2-5)$$

Linear dichroism effect is a phenomenon that when light propagates in an anisotropic material, light with different polarization directions experience different absorptions.

Birefringence effect is one of the most important magneto-optical properties of MF, which is commonly used in the MF-based photonic devices [62]. There have been a lot of investigations on the magneto-optical birefringence effect of MF [13-16, 63-71]. As discussed in Section 2.1.2, MF is a colloidal suspension of magnetic nanoparticles. The effective dielectric constant or refractive index of the MF is dependent on the dispersion state of the magnetic nanoparticles. In the absence of the external magnetic field, the ferromagnetic nanoparticles disperse uniformly in the liquid carrier and the MF as a whole exhibits homogeneity. In the presence of the external magnetic field, the homogenous state is broken and the situation changes. The agglomeration occurs to the ferromagnetic nanoparticles in the liquid carrier which leads to the phase separation between the nanoparticles and liquid carrier. Subsequently, the dielectric constant or refractive index of the MF is changed accordingly [72]. It has been discussed in Section 2.1.2, the higher the external magnetic field strength, the more significant the phase separation and then the greater the variation of the refractive index. Accompanied by the phase separation, the nanoparticles agglomerate and tend to form magnetic columns or magnetic chains along the direction of magnetic field to some extent, hence the MF becomes an anisotropic structure under the external magnetic field (Figure 2-4). The

shape of the magnetic nanoparticles in MF in the Figure 2-4 is ellipsoid for convenient understanding, but the actual shape of the nanoparticles is very close to sphere.

Figure 2-4 MF becomes anisotropic in the presence of external magnetic field

In this instance, the MF can be treated like a traditional optical crystal with optical axes. Since the magnetic columns or chains of the ferromagnetic nanoparticles are aligned along the magnetic field direction, the slow axis of the MF is also aligned along the magnetic field direction and in turn the fast axis of the MF is perpendicular to the magnetic field direction (Figure 2-5). The MF exhibits different refractive indices on the fast axis and slow axis. This phenomenon is referred to as the birefringence effect of MF, which follows a Langevin function as the magnetic field strength is increased [15, 73]. If the light is launched into the MF perpendicularly to the magnetic field direction, then it will fall into two orthogonal

polarized light beams, saying the extraordinary light (e-ray, whose electric vector orients parallel to the slow axis) and the ordinary light (o-ray, whose electric vector orients parallel to the fast axis). The two orthogonal linearly polarized light beams travel with different propagation constants due to the birefringence effect and a phase difference is accumulated over the thickness of the MF. Meanwhile, the e-ray and o-ray also experience different absorptions in the MF due to the anisotropic structure. This phenomenon is referred to as the dichroism effect of MF. The refractive index corresponding to the slow axis is n_e whilst the refractive index corresponding to the fast axis is n_o . Hence, the birefringence of MF is $B = n_e - n_o$. Usually, the birefringence effect and dichroism effect coexist in MF under external magnetic field.

Figure 2-5 Linear birefringence of MF

There have been a lot of discussions on the origin of the birefringence effect of MF [13, 14]. Two main theories were proposed to explain the physical mechanisms responsible for the birefringence effect of MF. One is particle orientation theory [64] which assumes the non-spherical individual ferromagnetic

nanoparticle in the colloid rotates and aligns along the external magnetic field direction and then causes the anisotropy and birefringence effect of MF as a whole. The other is formation theory [65] which considers the ferromagnetic nanoparticles form magnetic chains along the external magnetic field direction and then bring about the birefringence effect of MF. Further investigations found that MF exhibits the birefringence phenomenon even in the absence of external magnetic field. However, neither of the above theories could completely explain the origin of the zero field birefringence effect of MF. Later, Bakuzis proposed a dimer model to explain the zero field birefringence effect of MF, in which the nanoparticle chain structures were attributed to the spontaneous formation of dimers rather than monomers [66-68]. However, there were still discussions on the physical mechanism of the formation of zero field birefringence effect of MF.

The dependence of birefringence effect of MF on the nanoparticle size, nanoparticle concentration and temperature were also discussed [67, 69, 70]. Especially, the laser self-induced thermal effect on the birefringence effect of MF was also important to the practical MF-based devices such as magneto-optical sensors and modulators [74]. Besides, it was reported that the magnetic field induced birefringence effect was always accompanied by the dichroism effect, which also depended on the external magnetic field strength [15, 75].

The configuration of measuring the linear birefringence effect of MF is shown in Figure 2-6. Light of single wavelength from a tunable laser passes through the polarizer and becomes a linearly polarized light. Then the linearly polarized light passes through the MF film and becomes an elliptically polarized light due to the birefringence effect of MF. Subsequently, the analyzer is rotated for obtaining

the maximum intensity and minimum intensity of the light with the detector. The birefringence B can be given by [63]

$$B = \Delta n = \frac{\lambda}{2\pi d} \sin^{-1} \frac{2\sqrt{I_{\min}/I_{\max}} \operatorname{ch}(h_1 - h_2)}{1 + I_{\min}/I_{\max}} \quad (2-6)$$

where λ is the operating wavelength of the light; d is the thickness of the MF film, h_1 and h_2 are the magnetic field induced absorption coefficients of MF which can be expressed as the function of the magnetic field strength H ,

$$h_i(H) = \frac{1}{2} \ln \frac{I_0}{I_i} \quad (2-7)$$

where I_0 is the output intensity under zero magnetic field. This traditional method of measuring the birefringence effect of MF has taken account of the influence of the dichroism effect of MF. However, since the MF has a huge absorption coefficient and some reflection feeds back at the end surfaces of the optical components such as polarizer and analyzer, the light intensity received at the optical powermeter is not very stable. This disadvantage affects the accuracy of measurement.

Figure 2-6 Schematic diagram for measuring the linear birefringence effect of MF

2.1.4 Faraday Effect of Magnetic Fluid

Faraday effect is the most commonly used magneto-optical effect, which is often employed in electrical current sensor [76]. Figure 2-7 describes the principle of the Faraday effect. A linearly polarized light rotates its polarization plane when it travels in the Faraday material that exhibits Faraday effect [1]. The total rotated angle F is proportional to the length of the magnetic material d and the magnetic strength H . V is the Verdet constant of the Faraday material which describes the ability to rotate the linearly polarized light.

$$F = VHd \quad (2-8)$$

Figure 2-7 Scheme of Faraday effect

Faraday effect causes circular birefringence. Circular birefringence is a phenomenon that left circularly polarized light and right circularly polarized light propagate at different speeds in the optically active material. (As a comparison, linear birefringence is a phenomenon that the two orthogonally linearly polarized light beams propagate at different speeds in the optically active material.) Since the incident linearly polarized light can be treated as the composite of a left circularly

polarized light and a right circularly polarized light, the rotation of the polarization plane of the linearly polarized light caused by Faraday effect can be described by the theory of circular birefringence. Only pure circular birefringence is caused by the Faraday effect which means if a linearly polarized light is launched into the Faraday crystal, the polarization direction of the light will change with the propagation length but the polarization state (linearly polarized) will remain unchanged.

Faraday rotation is a nonreciprocal effect related to the direction of magnetic field H . Light coming from the opposite direction (Figure 2-7) causes a sign change in the F , which provides a possibility to measure the magnetic field direction. In this case, the magnetic field strength can be determined by means of measuring the Faraday rotation angle.

The schematic diagram of the polarimetric method for measuring the Faraday rotation angle caused by Faraday effect or circular birefringence (Figure 2-8) is similar to the one for measuring the linear birefringence (Figure 2-6), but the magnetic field direction is parallel to the light propagation direction.

Figure 2-8 Schematic diagram of the setup for measuring the Faraday effect of MF

Assuming the angle between the polarization direction of the polarizer and the one of the analyzer is α , the intensity measured by the detector is given as,

$$I = I_0 \cos^2(\alpha - F) \quad (2-9)$$

Then the polarization angle F can be determined and the magnetic field strength and the magnetic field direction can be further determined. Many other configurations for measuring the Faraday rotation are proposed, but the basic principle remains the same.

MF exhibits Faraday effect under external magnetic field [71, 77-81]. However, the condition of the Faraday effect of MF is different from the one of the linear birefringence effect of MF. The Faraday effect occurs when the light propagation direction is parallel to the magnetic field direction (Figure 2-9) whilst the linear birefringence effect occurs when the light propagation direction is perpendicular to the magnetic field direction (Figure 2-5).

Figure 2-9 Faraday effect of MF

The Verdet constant of the MF is estimated by using the setup in Figure 2-8 and the result is reported to be $122.43 \times 10^3 \text{ rad}/(\text{T m})$ [71]. The Verdet constant of the MF is 2-3 orders of magnitude larger than some traditional optical materials such as Flint glass, BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$), FR-5 glass and so on. However, the MF has large absorption coefficient, therefore the thickness of MF film is usually as thin as

several tens of microns (dependent on the concentration of MF). Assuming the thickness of MF film is $20\mu\text{m}$ and the external magnetic field strength is 100Oe , then the Faraday rotation angle caused by Faraday effect is about 0.024rad , which is very small.

2.1.5 Field Dependent Transmission of Magnetic Fluid

The transmittance of the MF can also be modulated by external magnetic field. This phenomenon is referred to as the field dependent transmission property of MF [82-89]. The field dependent transmission property of MF found some applications in the optical devices such as magnetic field sensor, switch and modulator [82, 88, 90]. The physical mechanism for the field dependent transmission of MF can be divided into two cases, saying the transverse field transmittance and the longitudinal field transmittance [83].

As for the case of transverse field transmittance, the arrangement of the magnetic field direction and the light propagation direction are the same as the one in Figure 2-5. The magnetic field direction is perpendicular to the light propagation direction. In this case, magnetic nanoparticles form chains along the external magnetic field and the MF as a whole becomes anisotropic. It is reported in the literatures that the anisotropic pattern should be responsible for the field dependent transmission property of MF [82, 83]. The light beams with different polarization directions experience different absorptions, which is mentioned in the Section 2.1.3 as dichroism effect of MF. The variation trends of the field dependent transmission properties of MF with different carriers are also different [87]. As for the kerosene-based MF, the transmittance of the ordinary light (o-ray), whose electric field vector

is perpendicular to the magnetic field direction, increases with the external magnetic field strength; whilst the transmittance of the extraordinary light (e-ray), whose electric field vector is parallel to the magnetic field direction, decreases with the external magnetic field strength. As for the transformer oil-based MF, the transmittances of both the e-ray and o-ray decrease with the external magnetic field strength.

As for the case of longitudinal field transmittance, the arrangement of the magnetic field direction and the light propagation direction are the same as the one in Figure 2-9. The magnetic field direction is parallel to the light propagation direction. In this case, magnetic nanoparticles form magnetic columns under external magnetic field and the MF as a whole can be treated as an isotropic material to the light. It is reported in the literatures that the scattering and geometric shadowing effect should be responsible for the field dependent transmission property of MF. The evolution of the formation pattern of the magnetic columns from a disordered phase to a hexagonal structure and further to a labyrinthine pattern was also reported [82, 84]. The transmittance of the MF decreases with external magnetic field strength.

In addition to the physical mechanism, other investigations on the field dependent transmission property of MF were also carried out. The influence factors such as the sweep rate of the magnetic field, the thickness of MF film, the concentration of MF on the field dependent transmission property of MF were also reported [88]. Besides, the response time of the field dependent transmission property was also experimentally observed and discussed [85, 89].

2.1.6 Thermal Lens Effect of Magnetic Fluid

Thermal lens effect was first observed in 1964 when Gordon observed the Raman scattering in a liquid sample [91]. It is a phenomenon that is related to the thermo-optical effect caused by the laser itself power or energy. The transmission medium or optical component on the transmission path is heated by the laser, subsequently, their density is changed and further their corresponding refractive index is changed as a result. The effect of the heating area of the medium is equivalent to an optical lens with negative focal length. The beam divergence of the laser will expand after this thermal lens. The thermal lens effect is not an immediate response but a time dependent process, since it will take some time to establish the new thermal equilibrium.

The thermal lens effect also exists in MF [24, 74]. The laser heats the MF and creates a gradient temperature field when it passes through the MF. As a result, the nanoparticles redistribute in the heating area of MF, where the refractive index changes due to the thermo-optical effect. The thermal effect of MF affects the beam divergence of the laser, which is often considered as a harmful side effect. The quasisteady diffraction patterns of the laser beam were observed in the experiment [24]. It was also reported that, the thermal lens effect can be suppressed in the presence of external magnetic field in terms of the divergence angle of the laser beam [24].

2.2 Optical Fibers

Fiber optics is a modern branch of traditional optics, which describes the behaviors and properties of the light in a special catalogue of circular waveguide,

namely optical fibers. It first began in 1950s. With the rapid development of optical fiber communication technology, its content grows more abundant and deeper. The rapid development of optical fiber technology is benefited from the fiber alignment technology. After that, a whole series of optical fiber components have been developed such as optical fiber coupler, isolator, wavelength division multiplexer (WDM), circulator, filter, reflect mirror, collimator, modulator and the list goes long. Meanwhile, a whole series of optical fibers have also been developed to fulfill the requirements of some special applications such as single mode fiber (SMF), multimode fiber (MMF), polarization maintaining fiber (PMF), dispersion compensation fiber (DCF), Erbium doped fiber (EDF), dual core or multi core fiber and so on. Recently, a new family of optical fibers emerges, that is photonic crystal fiber (PCF). In this Section, we will briefly introduce several kinds of optical fiber that are used in our experiment.

2.2.1 Single Mode Fiber

Single mode fiber is actually a terminology in the area of optical fiber communication, in which the optical fibers can be divided into single mode fiber and multimode fiber in terms of the number of the transmission modes designed for their operating states. Mode is a concept in wave optics, which describes the possible stable distribution states of the electric magnetic field of the light in the transverse cross section of an optical fiber. The modes of an optical fiber are solved from the Maxwell equation groups under some boundary conditions. The number of the modes depends on the operating wavelength of the light and the parameters of the fiber structure. The fiber structure can be described by normalized frequency V

$$V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2} \quad (2-10)$$

where λ is the operating wavelength. a is the radius of the core (Figure 2-10). As for the single mode fiber, the diameter of the core is about 4-12 μm . n_1 is the refractive index of the core whilst n_2 is the refractive index of the cladding, where $n_1 > n_2$.

Figure 2-10 Typical structure of a step-index single mode fiber

If the condition $V \leq 2.40483$ is fulfilled, only one mode exists in the fiber. The number of the modes can be estimated approximately by $N = V^2/2$ (not accurate). Eq.(2-10) shows that the normalized frequency (V) is inversely proportional to the operating wavelength of the light (λ). It means for a single mode fiber, it may become a multimode fiber at a shorter wavelength. For example, the traditional single mode fiber (e.g. G652) is designed for the wavelength bands in optical communication, saying the 1310nm (O band) and 1550nm (C band) transmission windows. Its cut-off wavelength is about 1260nm, which means if the operating wavelength of the light is longer than the cut-off wavelength, the fiber will operate on a single mode state; otherwise, if the operating wavelength of the light is shorter than the cut-off wavelength, the fiber will operate on a multimode

state. Therefore, the traditional single mode fiber operates on a single mode state for the near-infrared light (1310nm window & 1550nm window) but operates on a multimode state for the visible light (400-760nm).

The multimode fibers designed for optical communication usually have cores with larger diameters, whose typical values are 50 μm and 62.5 μm . The multiple transmission modes in the multimode fiber possess different individual distribution patterns of electric magnetic field and exhibit different propagation constants, which can be treated as different light rays propagating in the same fiber. Figure 2-11 shows the photos of the cross sections of a single mode fiber and a multimode fiber.

Figure 2-11 Photos of cross sections of (a) a single mode fiber and (b) a multimode fiber

From the perspective of geometric optics, the principle of confining light in the core of the fiber is due to the total internal reflection. The total internal reflection is an optical phenomenon that when the incident light is launched from an optically denser medium (n_1) to an optically thinner medium (n_2), if the incident angle is larger than a certain angle (critical angle), all the light will be reflected back to the

optically denser medium and no light will enter into the optically thinner medium. Since the core diameter of single mode fiber (4-12 μm) is relative small, it is easier to fulfill the condition of total internal reflection and light propagates along only one path that is the single mode (Figure 2-12(a)). The core diameter of multimode fiber (typically 50 μm or 62.5 μm) is relatively large, so the light can propagate along multiple paths that are multiple modes (Figure 2-12(b)).

Actually, in the single mode fiber, there is a pair of modes (TE mode & TM mode) propagating along the fiber simultaneously. In the theory of scalar approximation or wave coupling approximation, the two modes are called degenerate linearly polarized modes (LP_x mode and LP_y mode) that possess the same frequency and the same propagation constant. The vibration directions of the two linearly polarized modes are orthogonal. In the area of optical fiber communication, the two modes are treated as one mode, so the fiber is often named as single mode fiber.

Figure 2-12 Schematic diagram of light propagating in a single mode fiber and a multimode fiber

2.2.2 Polarization Maintaining Fiber

As reviewed in the last Section, a circularly symmetric single mode fiber can usually support a pair of two orthogonal linearly polarized modes or two orthogonal circularly polarized modes. Ideally, if the fiber is perfectly circularly symmetric, which means the geometric shape is ideally circular and the distribution of the refractive index is uniform, the two orthogonal modes will propagate at the same speed and the polarization states will not change. However, a practical fiber is not ideally circularly symmetric due to the manufacturing technology or bend of the fiber (birefringence of the waveguide), while the distribution of the refractive index is not ideally uniform due to the residual stress (birefringence of the material), so the two orthogonal modes will couple to each other which lead to the change of the polarization states and the difference of the propagating speeds of the two modes. This phenomenon is called polarization mode dispersion (PMD) or birefringence effect of the fiber.

This problem can be solved by using polarization maintaining fiber [92] which is a kind of high birefringence fiber (HBF) or low birefringence fiber (LBF). For a common single mode fiber, the birefringence B is $10^{-6} < B < 10^{-5}$; If the birefringence of the fiber is $B < 10^{-6}$, it is classified as low birefringence fiber; If the birefringence of the fiber is $B > 10^{-5}$, it is classified as high birefringence fiber. There are many designs of the polarization maintaining fiber [6]. One of the most commonly used is the panda fiber (Figure 2-13) and its birefringence is about 3.3×10^{-4} .

Similar to traditional optical crystal, polarization maintaining fiber has optical axes which are termed as fast axis and slow axis, respectively. If the linearly polarized light is launched into the fiber with its polarization direction parallel to either the fast axis or the slow axis of the polarization maintaining fiber, the polarization state of the light will remain unchanged during the propagation along the fiber length. In other words, the polarization maintaining fiber can only preserve the linear polarization state of the light. But, if the polarization direction of the light is aligned with neither the fast axis nor the slow axis, the polarization state of the light will change with the propagation length.

This polarization maintaining fiber is a high birefringence fiber in nature (Figure 2-13). Similarly to the optical crystal that is reviewed in Section 2.1.3, light with arbitrary polarization state launched into the polarization maintaining fiber will fall into two linearly polarized components. The polarization direction of one linearly polarized component is parallel to the fast axis of the polarization maintaining fiber whilst the polarization direction of the other one is parallel to the slow axis of the polarization maintaining fiber. A phase difference is introduced by the intentionally created birefringence of the fiber, which can be calculated by

$$\varphi = \frac{2\pi}{\lambda} BL \quad (2-11)$$

where BL is the optical path difference (OPD); B and L are the birefringence and the length of the fiber, respectively. Eq.(2-11) shows that the amount of the introduced birefringence can be adjusted by controlling the length of the fiber. From this perspective, the polarization maintaining fiber can be considered as a variable wave plate or a variable phase retardation plate.

In the experiments in this thesis, the polarization maintaining fiber is employed as atypical kind of high birefringence fiber to introduce phase difference between the two orthogonal linearly polarized modes. It is not used for maintaining the polarization state of the light. Therefore, the polarization maintaining fiber used in the experiment can be replaced by any kind of high birefringence fiber.

2.2.3 Photonic Crystal Fiber

Photonic crystal fiber (PCF) or holly fiber, microstructured fiber is a newly emerged family of optical fibers. It is created by introducing 2D photonic crystal as well as a defect into the cross section of an optical fiber, so the light is confined in the defect and propagates along the fiber length. Usually, the 2D photonic crystal is realized as a periodic air-hole structure in the PCF. Different from traditional optical fibers, the properties of PCF can be flexibly designed by manipulating the air-hole structures for different applications. Figure 2-14 gives some typical examples of PCFs.

Generally, PCFs can be divided into two classes according to their operating principles. One is index guiding fiber [93, 94] and the other is photonic bandgap fiber [95, 96]. The index guiding fiber has a solid core and the average refractive index of the air-hole cladding is lower than the refractive index of the core, so the

operating principle is total internal reflection, which is the same as the one of traditional optical fiber. The photonic bandgap fiber has a hollow core and the average refractive index of the air-hole cladding is higher than the refractive index of the core, so the operating principle is photonic bandgap effect. Recently, all solid photonic bandgap fiber is developed. The structure of all solid photonic bandgap fiber is similar to the structure of the hollow core photonic bandgap fiber, but the air-holes are replaced with rods with high refractive index.

Figure 2-14 Cross sections of some typical PCFs

PCFs have many unique properties such as large mode area, endless single mode, controllable dispersion property, high nonlinear coefficient, high

birefringence effect, large numerical aperture, ultralow temperature coefficient and so on [4]. Therefore, PCFs find many applications such as fiber lasers and amplifiers [97], fiber sensors [98], fiber gratings [99], delivering mid and far infrared light [100], supercontinuum generation [101], nonlinear applications [102] and so on. Figure 2-15 shows the published papers and citations on the topic of PCFs are increasing with years. Here we briefly review the various applications of the PCF in the area of optical fiber sensors.

Figure 2-15 Published papers and citations on the topic of PCF

The unique property of PCFs is their air-hole structures, in which various sensitive materials including solid, liquid and gas can be filled to realize sensors. For example, Wolinski's research group filled liquid crystal into the air-holes of PCFs to realize temperature sensors [103]; Various gasses including CO₂, CH₄, H₂, etc were filled into PCFs to realize gas sensors [104]; Metal nanoparticles were coated in the inner wall of the air-holes to realize sensors based on surface plasmon resonance (SPR) [105] and surface enhanced Raman scattering (SERS) [106].

Recently, there were some sensors based on selectively or partially filled the air-holes of PCFs and their sensitivities were further improved [107].

Another unique advantage of PCFs is their ultralow temperature coefficient [108]. The core and cladding of traditional fiber are made up of doped silica and pure silica respectively, which exhibit different thermal expansion coefficients. This thermal sensitive property of the fiber may cause cross sensitivity problem to the sensor. However, the core and cladding of PCF are made up of the same material, pure silica. Hence, the temperature coefficient of PCF is 3 orders less than the one of traditional fiber.

The air-holes of PCFs will be collapsed during the process of fusion splice (Figure 2-16). The PCF with air-hole collapse becomes a silica rod. Light propagating in this PCF with air-hole collapse will generate modal interference and evanescent field, both of which can be used to realize sensors [109]. One of their most typical applications is the structure of single mode fiber-multimode fiber-single mode fiber (SMF-MMF-SMF), which is based on the PCF with collapsed air-holes. Taking advantage of this “sandwich structure”, Mach-Zehnder interferometer has been developed for various sensing measurements such as refractive index, bend, strain and so on.

Figure 2-16 Collapsed PCF during the fusion splice (PCF, LMA-10 Photonics A/S)

There are also some optical fiber sensors based on special PCFs. For example, dual-core or multi-core PCFs have been developed for sensing applications [110]. The light propagating in the dual-core or multi-core fiber will couple to each other. This kind of PCFs can be used for diverse sensing measurements such as temperature, strain, force and so on. Especially, it can be used for directional bend measurement. Similarly, ring core fiber was also reported for sensing measurement [111]. Besides, Bragg fiber has been reported for biosensing applications [112]. Various high birefringence PCFs or polarization maintaining PCFs were employed in optical fiber gyros (FOGs) to reduce the thermal coefficient [113].

In the following Chapter, we will introduce two types of magnetic field sensors by combining the MF with PCF. One is based on the PCF with air-hole collapse and the other is based on the MF filled PCF.

2.3 Optical Fiber Interferometry

In Section 2.1, we have reviewed the magneto-optical properties of MF. In Section 2.2, we have reviewed some commonly used fibers that are also used in our experiment. In this Section, we will discuss some fiber demodulation configurations, i.e. optical fiber interferometry, for demodulating the sensing signals. We will introduce the commonly used optical fiber interferometers in this Section including Fabry-Perot interferometer (FPI), Mach-Zehnder interferometer (MZI), Michelson interferometer (MI) and Sagnac interferometer (SI). All the interferometers work on the principles of two-beam interference or multi-beam interference. The phases of the beams for interference are influenced by the measured physical parameters.

Therefore, by measuring the change in the phase of the light, the corresponding physical parameters can be determined.

2.3.1 Fabry-Perot Interferometer

The operating principle of the Fabry-Perot interferometer is multi-beam interference. The cavity of Fabry-Perot interferometer is composed of two parallel, flat mirrors. Light launched into the cavity is reflected back and forth by the two mirrors (Figure 2-17). Then all the reflected or transmitted beams will interfere together. There is a phase difference φ between the two adjacent reflected beams which is given by

$$\varphi = \frac{2\pi}{\lambda} 2nd \cos \theta \quad (2-12)$$

where d is the cavity length. n is the refractive index of the medium between the two mirrors. λ is the operating wavelength. θ is the incidence angle.

Figure 2-17 Diagram of a Fabry-Perot interferometer

Assuming the reflectivity of the two mirrors are the same, the transmittance function can be given by [114]

$$T = \frac{1}{1 + F \sin^2 \frac{\phi}{2}} \quad (2-13)$$

where F is the coefficient of fineness, which is determined by the reflectivity R

$$F = \frac{4R}{(1-R)^2} \quad (2-14)$$

T is a function of R . The reflectivity of a common glass face (for example, a fiber end face) is only 4%, so the visibility of the transmission spectrum is very low. In order to increase the visibility, materials with high reflectivity are needed to coat on the mirrors such as metals or optical films. This is the difficulty for manufacturing fiber type Fabry-Perot interferometer.

In order to fulfill the condition of optical interference, the cavity length of a Fabry-Perot interferometer should be shorter than the coherent length of a broadband light source, which is in an order of tens to hundreds of microns. This will also increase the difficulty for manufacturing the fiber type Fabry-Perot interferometer.

2.3.2 Mach-Zehnder Interferometer

The operating principle of a Mach-Zehnder interferometer is two-beam interference. Figure 2-18 schematically shows the diagram of a typical Mach-Zehnder interferometer. Light is split into two beams by the beam splitter. The split two beams travel in two separate paths, which are denoted as reference arm and sensing arm. Subsequently, the two beams recombine again at the beam combiner

with a phase difference φ and interfere. Often the case, φ is a wavelength dependent function induced by the external physical parameters. The output spectrum of the Mach-Zehnder interferometer can be expressed as [114]

$$I(\lambda) = I_s + I_r + 2\sqrt{I_s I_r} \cos \varphi \quad (2-15)$$

where I_s and I_r are the intensities of the sensing beam and reference beam.

Figure 2-18 Diagram of Mach-Zehnder interferometer (a) free space type (b) fiber type

The typical transmission spectrum is given in Figure 2-19, which is an approximately sinusoidal function of wavelength λ . Thus, the measured physical parameters can be observed easily by measuring the wavelength of the output spectrum of the Mach-Zehnder interferometers. By using a laser of single

wavelength as the light source, the Mach-Zehnder interferometer can be changed from the spectrum output type to the intensity output type, which can be used in dynamic applications. The parameter of visibility (or fringe contrast) of the interference spectrum can be defined as

$$V = \frac{I_M - I_m}{I_M + I_m} \quad (2-16)$$

where

$$I_M = I_s + I_r + 2\sqrt{I_s I_r} \quad (2-17a)$$

$$I_m = I_s + I_r - 2\sqrt{I_s I_r} \quad (2-17b)$$

When $I_M = I_m$, i.e. $I_s = I_r$, the maximum visibility $V=1$ is obtained.

In order to realize an optical fiber Mach-Zehnder interferometer, the beam splitter and beam combiner in Figure 2-18(a) are replaced with two fiber couplers in Figure 2-18(b). Assuming a 3-dB coupler is used and the transmission loss is neglected, the output intensity can be further expressed as,

$$I_1 = I_0 \cos^2 \frac{\varphi}{2} \quad (2-18a)$$

$$I_2 = I_0 \sin^2 \frac{\varphi}{2} \quad (2-18b)$$

where I_1 and I_2 are the intensities of the two output ports of the coupler, respectively (Figure 2-18(b)). To fulfill the conditions of interference, the optical path difference between the sensing arm and reference arm should be smaller than the coherent length of the broadband light source. The typical value of length difference is smaller than 1mm, which is difficult to realize by the fiber technology.

Figure 2-19 Transmission spectrum of Mach-Zehnder interferometer

2.3.3 Michelson Interferometer

The operating principle of the Michelson interferometer is two-beam interference, which is similar to Mach-Zehnder interferometer. Hence, the formulas deduced in Section 2.3.2 are also applicative to Michelson interferometer. The difference between Mach-Zehnder interferometer and Michelson interferometer exists in the configuration. The two beams for interference in Mach-Zehnder interferometer are transmission type, while in Michelson interferometer they are reflection type.

To realize fiber type Michelson interferometer, a 3dB coupler can be used to replace the beam splitter. The difficulties lie in matching the fiber length like Mach-Zehnder interferometer and fabricating their fiber ends with high reflectivity.

Figure 2-20 Diagram of Michelson interferometer (a) free space type (b) fiber type

2.3.4 Sagnac Interferometer

The operating principle of the Sagnac interferometer is two-beam interference. As shown in Figure 2-21, the two beams split by the beam splitter counterpropagate along the Sagnac loop and accumulate phase difference due to the birefringence within the fiber loop. The birefringence could be intrinsic birefringence of the fiber or induced birefringence caused externally like force, bend or twist. Then, the two beams recombine again at the same splitter and interfere. The phase difference exists between the two orthogonal guided modes, which is given by

$$\varphi = \frac{2\pi}{\lambda} BL \quad (2-19)$$

where λ is the operating wavelength of the light; B is the birefringence of the fiber; L is the length of the birefringent fiber.

Figure 2-21 Diagram of Sagnac interferometer (a) free space type (b) optical fiber type

The formulas deduced in Section 2.3.2 are also applicative to Sagnac interferometer. Since the two beams for interference in Sagnac interferometer propagate along the same path and experience the same loss, it is easy to obtain high visibility of the transmission spectrum. The fiber type Sagnac interferometer can be realized simply by just splicing the two output ports of a 3-dB coupler (Figure 2-21(b)).

The advantages and disadvantages of the above optical fiber interferometers are compared in Table 2-1

Table 2-1 Advantages and disadvantages of the optical fiber interferometers

Type	Advantages	Disadvantages
FPI	High fineness High visibility	Difficult in manufacturing short cavity shorter than coherent length of light source
MZI	Sensing arm and reference arm are separate (transmission type)	Difficult in matching the fiber lengthss of sensing arm and reference arm
MI	Sensing arm and reference arm are separate (reflection type)	Difficult in matching the fiber length of sensing arm and reference arm
SI	Two beams propagate in same path, experience same loss	Two beams for inference are not separate

2.4 Chapter Summary

In Section 2.1, we have reviewed various properties of MF and their applications. We have focused on the magneto-optical properties of MF, especially the tunable refractive index property and the linear birefringence effect. In addition to the magneto-optical properties, MF has both the fluidity like liquid and the strong magnetism like solid material. These unique characteristics make MF a promising candidate for fiber optics applications.

In Section 2.2, the basic knowledge of optical fibers including traditional fibers and photonic crystal fibers are discussed. Three kinds of optical fibers are discussed for the potential combination with MF. In section 2.3, the optical fiber interferometry is discussed as the potential demodulation schemes.

Considering the characteristics of MF and the advantages or disadvantages of the various optical fiber interferometers, some kinds of magnetic field sensors

and magneto-optical devices are proposed. For example, MF has magnetically controllable birefringence effect, so it can be applied in an optical fiber Sagnac interferometer for sensing purpose; MF has tunable refractive index and fluidity, so it has potential to be filled into the air-holes of photonic crystal fiber to realize a magnetic field sensor based on the photonic bandgap effect; Besides, MF can also interact with the evanescent field of photonic crystal fiber with air-hole collapse. The following Chapters will be focusing on the development of these MF-based optical fiber devices, especially the magnetic field sensors and magneto-optical modulators. The properties of MF used in the experiment and the operating principle are summarized in Table 2-2. In the following Chapters, we will verify the these proposed MF-based optical fiber devices and try to improve their performance.

Table 2-2 Proposed MF-based optical fiber magnetic field sensors and magneto-optical modulators

Applications	Configurations	Properties of MF	Principles
Magnetic field sensors	SI	Birefringence	Interference
	MZI	Refractive index	Evanescent field
	Transmission	Refractive index	Bandgap effect
Magneto-optical modulators	SI	Birefringence	Interference
	Polarimeter	Birefringence	Interference

Chapter 3 Analysis of Birefringence Effects in Optical Fiber Sagnac Interferometer

3.1 Introduction

After reviewing the various magneto-optical properties of MF in Chapter 2, we can see that the MF is a promising functional material and excellent candidate for photonic devices. Out of various magneto-optical properties of MF, the refractive index tunability and the birefringence effect are the most intensively investigated. There were already some applications such as magnetic field sensors and magneto-optical modulators based on the tunable refractive index of MF [61, 115], however, the applications based on the birefringence effect of MF were rarely reported. The main challenges were that the transmission loss of MF was too huge and the phase difference induced by the birefringence effect of MF was too small. Therefore, we need to find a suitable demodulation scheme for the use of birefringence effect of MF. After comparing various kinds of optical fiber interferometers, we consider an optical fiber Sagnac interferometer (OFSI) as a better choice. Because, in the OFSI, the two light beams for interference counterpropagate along exactly the same path, they experience the same transmission loss. So there is no need to balance the intensities of the two light beams for interference. Meanwhile, the OFSI is sensitive to the change of birefringence, therefore it can be competent for demodulating the birefringence

effect of MF. As reviewed in Chapter 2, MF has both linear birefringence effect and circular birefringence effect (Faraday effect), so we will investigate both the linear birefringence effect and circular birefringence in the OFSI in this Chapter.

OFSIs, which are also known as fiber loop mirrors (FLMs), have been widely demonstrated as fiber devices in optical fiber communication and optical fiber sensors in a number of applications owing to its simple structure, easy fabrication and high flexibility [62, 73, 98, 108, 116-121]. For example, Ouyang proposed a wavelength tunable mode lock fiber laser with a high birefringence Sagnac loop which served as a tunable filter [116]; Mortimore demonstrated the applications of OFSI as fiber loop reflectors [122]; Optical fiber switches [123] and modulators [124-126] were also demonstrated. Besides, the nonlinear optical effects were also investigated in the OFSIs [127, 128]. In particular, the OFSI sensors for diverse parameter measurements attract the most research interests, such as temperature, twist, load, curvature, strain, magnetic field and so on [73, 98, 108, 117-121]. Here, the OFSIs are based on the interference between the two orthogonal modes induced by the high birefringence existing within the Sagnac loop. Another kind of OFSI, which is usually used in optical fiber gyroscope, is based on the Sagnac effect whilst the interference occurs between the two light beams counterpropagating along the Sagnac loop. These two kinds of OFSIs are significantly different from mechanisms to applications. The one we used in this thesis is the former one. Among the literatures, one of the main efforts is devoted to improve the sensitivities of the OFSI sensors with various methods. For instance, different types of HBFs including all kinds of traditional HBFs and newly emerged high birefringence photonic crystal fibers (PCFs) were incorporated into the OFSIs

to compare the sensitivities [118, 120]; Special treating processes like side polishing, chemical etching or tapering were applied to the fiber in the Sagnac loop to explore the possibility [120]; Functional materials such as liquid crystal, alcohol and magnetic fluid were also used to enhance the sensitivity [73, 117, 121]. In this Chapter we try the use of the low birefringence fiber in the OFSI to explore the possibility for improving the sensitivity of OFSI-based sensors. Meanwhile, the method of applying the birefringence properties of MF in OFSIs is also verified.

3.2 Theory of Optical Fiber Sagnac Interferometer

The schematic diagram of a typical high birefringent optical fiber Sagnac interferometer is shown in Figure 3-1.

Figure 3-1 Schematic diagram of a typical highly birefringent OFSI

It is fabricated simply by splicing the two output ports of a single mode fiber (SMF) coupler with a section of high birefringence fiber to form a Sagnac loop. The

light from a light source is split into two beams by the fiber coupler, which counterpropagate along the Sagnac loop, then recombine and interfere at the coupler again. Assume the birefringence within the Sagnac loop is B . This birefringence could be an intrinsic birefringence of the fiber caused by anisotropic stress or anisotropic structure like a traditional high birefringence fiber (e.g. panda fiber) and could also be an induced birefringence caused by mechanical forces such as transverse force, twist or bend on the fiber. The Jones Matrix method is employed to analyze the characteristics of this highly birefringent Sagnac interferometer [129, 130].

Light is launched into the port 1 of the coupler, whose amplitude of the electric field vector is E_{in} , and then is split into two light beams with their according amplitudes of the electric field E_3 and E_4 . If all the insertion loss of the Sagnac loop is neglected in an ideal condition, E_3 and E_4 can be obtained as

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{1-K} & j\sqrt{K} \\ j\sqrt{K} & \sqrt{1-K} \end{bmatrix} \begin{bmatrix} E_{in} \\ 0 \end{bmatrix} \quad (3-1)$$

where K is the power splitting ratio or coupling ratio of the coupler for the light beam propagating in the clockwise direction. E_3 and E_4 propagates along the loop clockwise and counterclockwise respectively, then accumulate phase difference through the high birefringence fiber. After E_3 and E_4 travel along the loop but before they re-enter into the coupler again, their amplitudes of electric field vectors become E'_4 and E'_3 , which can be given by [129, 130]

$$E'_3 = R(\theta_2)JR(-\theta_1)E_3 = J_{cw}E_3 \quad (3-2a)$$

$$E'_4 = R(\theta_1)JR(-\theta_2)E_4 = J_{ccw}E_4 \quad (3-2b)$$

where

$$R(\theta_i) = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \\ \sin \theta_i & \cos \theta_i \end{bmatrix} (i=1,2) \quad (3-3)$$

$R(\theta_i)$ is the rotation matrix. As shown In Figure 3-1, θ_1 is the angle between the polarization direction of the light propagating clockwise and the fast axis of the high birefringence fiber at one end of the high birefringence fiber; similarly θ_2 is the angle between the polarization direction of the light propagating counterclockwise and the fast axis of the high birefringence fiber at the other end of the high birefringence fiber;

$$J = \begin{bmatrix} \exp(-j\frac{\pi BL}{\lambda}) & 0 \\ 0 & \exp(j\frac{\pi BL}{\lambda}) \end{bmatrix} \quad (3-4)$$

J is the Jones Matrix of the high birefringence fiber or any birefringent component. Where, B is the birefringence of the high birefringence fiber; L is the length of the high birefringence fiber; λ is the operating wavelength of the light.

Substitute the Eq.(3-3) and (3-4) into Eq.(3-2a) and Eq.(3-2b), subsequently, the Jones Matrixes of the Sagnac loop for the light beams propagating clockwise (J_{cw}) and counterclockwise (J_{ccw}) are deduced as

$$J_{cw} = \begin{bmatrix} \cos \theta_1 \cos \theta_2 e^{-j\frac{\pi BL}{\lambda}} + \sin \theta_1 \sin \theta_2 e^{j\frac{\pi BL}{\lambda}} & \sin \theta_1 \cos \theta_2 e^{-j\frac{\pi BL}{\lambda}} - \cos \theta_1 \sin \theta_2 e^{j\frac{\pi BL}{\lambda}} \\ \cos \theta_1 \sin \theta_2 e^{-j\frac{\pi BL}{\lambda}} - \sin \theta_1 \cos \theta_2 e^{j\frac{\pi BL}{\lambda}} & \sin \theta_1 \sin \theta_2 e^{-j\frac{\pi BL}{\lambda}} + \cos \theta_1 \cos \theta_2 e^{j\frac{\pi BL}{\lambda}} \end{bmatrix} \quad (3-5a)$$

$$J_{ccw} = \begin{bmatrix} \cos \theta_1 \cos \theta_2 e^{-j\frac{\pi BL}{\lambda}} + \sin \theta_1 \sin \theta_2 e^{j\frac{\pi BL}{\lambda}} & \cos \theta_1 \sin \theta_2 e^{-j\frac{\pi BL}{\lambda}} - \sin \theta_1 \cos \theta_2 e^{j\frac{\pi BL}{\lambda}} \\ \sin \theta_1 \cos \theta_2 e^{-j\frac{\pi BL}{\lambda}} - \cos \theta_1 \sin \theta_2 e^{j\frac{\pi BL}{\lambda}} & \sin \theta_1 \sin \theta_2 e^{-j\frac{\pi BL}{\lambda}} + \cos \theta_1 \cos \theta_2 e^{j\frac{\pi BL}{\lambda}} \end{bmatrix} \quad (3-5b)$$

Then the light beams for interference (i.e. E'_4 and E'_3) re-enter into the coupler and produce interference fringes. The amplitudes of the electric field vectors for the light beams that coming out from port 1 (E_{1out}) and port 2 (E_{2out}) can be given by

$$\begin{bmatrix} E_{1out} \\ E_{2out} \end{bmatrix} = \begin{bmatrix} \sqrt{1-K} & j\sqrt{K} \\ j\sqrt{K} & \sqrt{1-K} \end{bmatrix} \begin{bmatrix} E'_4 \\ E'_3 \end{bmatrix} \quad (3-6)$$

From Eq.(3-6), we can deduce further and obtain

$$E_{1out} = \sqrt{1-K} E'_4 + j\sqrt{K} E'_3 = j\sqrt{K} J_{cw} E_3 + \sqrt{1-K} J_{ccw} E_4 \quad (3-7a)$$

$$E_{2out} = j\sqrt{K} E'_4 + \sqrt{1-K} E'_3 = \sqrt{1-K} J_{cw} E_3 + j\sqrt{K} J_{ccw} E_4 \quad (3-7b)$$

Therefore, the intensities of the reflection light (I_{1out}) and transmission light (I_{2out}) are deduced as

$$I_{1out} = E_{1out} \cdot E_{1out}^* = 4K(1-K)[1 - \sin^2(\theta_1 - \theta_2) \cos^2(\frac{\pi BL}{\lambda})] I_{lin} \quad (3-8a)$$

$$I_{2out} = E_{2out} \cdot E_{2out}^* = [(1-2K)^2 + 4K(1-K) \sin^2(\theta_1 - \theta_2) \cos^2(\frac{\pi BL}{\lambda})] I_{lin} \quad (3-8b)$$

where $I_{lin} = E_{lin} \cdot E_{lin}^*$ is the light intensity of the input light.

In practice, usually, a 3dB coupler is employed in the experiment, therefore $K=0.5$. Then the relative reflectivity (R) and relative transmissivity (T) can be obtained as

$$R = \frac{I_{1out}}{I_{1in}} = 1 - \sin^2(\theta_1 - \theta_2) \cos^2\left(\frac{\pi BL}{\lambda}\right) = 1 - \sin^2(\theta_1 - \theta_2)(1 - \cos \varphi) \quad (3-9)$$

$$T = \frac{I_{2out}}{I_{1in}} = \sin^2(\theta_1 - \theta_2) \cos^2\left(\frac{\pi BL}{\lambda}\right) = \sin^2(\theta_1 - \theta_2)(1 - \cos \varphi) \quad (3-10)$$

where $\varphi = 2\pi BL/\lambda$ is the phase difference caused by the high birefringence fiber.

Figure 3-2 Typical transmission spectrum of an OFSI

In practice, we usually use the transmission spectrum instead of the reflection spectrum of the OFSI for convenient measurement. Figure 3-2 shows a typical transmission spectrum of the OFSI, which is an approximately sinusoidal waveform. The fringe contrast or peak-to-peak ratio is dependent on the item $\sin^2(\theta_1 - \theta_2)$. Usually, a polarization controller (PC) is inserted into the Sagnac loop to adjust θ_1 and θ_2 so that the fringe contrast can reach its maximum, which can be as high as 30-40dB. The period of the transmission spectrum is dependent on

the phase difference φ . The dip wavelengths of the transmission spectrum also shift with the phase difference, which can be monitored for sensing measurement. If the OFSI is used as a sensor, the dip wavelength shift of the spectrum should be smaller than the period of the transmission spectrum. In this case, the period of the transmission spectrum is also named as free spectral range (FSR) of the OFSI. The dynamic range of the OFSI-based sensor is often defined by the FSR.

If the condition $\varphi = 2\pi m$ (m is an integer which represents the fringe order of the transmission spectrum) is fulfilled, the wavelength of the m -th order dip can be obtained as

$$\frac{BL}{\lambda_m} = m \quad (3-11a)$$

Similarly, the wavelength of $m+1$ -th order dip is

$$\frac{BL}{\lambda_{m+1}} = m + 1 \quad (3-11b)$$

Therefore, the period of the transmission spectrum (S) can be calculated as the spectral spacing between the two adjacent transmission dips

$$S_m = \lambda_{m+1} - \lambda_m \approx \frac{\lambda^2}{BL} \quad (3-12)$$

where $\lambda = (\lambda_m + \lambda_{m+1})/2$ is the average wavelength of the two adjacent dip wavelengths, $\lambda^2 \approx \lambda_m \lambda_{m+1}$. Eq.(3-12) shows that the period of the transmission spectrum is inversely proportional to the optical path difference (BL), i.e. inversely proportional to the birefringence B and the length of the birefringent fiber L . If the birefringence is too small or the length of the birefringent fiber is too short, the period will be too large to extend the spectral range of the measurement devices. If

BL is too large, the period is too small which will lead to a small dynamic range.

Hence, the optical path difference needs to be optimized in a suitable range.

The sensitivity of the OFSI-based sensor is defined by the dip wavelength shift of the transmission spectrum. From Eq.(3-11a), the dip wavelength shift can be given by

$$\Delta\lambda_m = \Delta BL/m \quad (3-13)$$

From Eq.(3-13), we can see that the sensitivity of the OFSI-based sensor is inversely proportional to the fringe order m . Therefore, in order to obtain a better sensitivity, the transmission dip on the longer wavelength side can be used.

3.3 Effects of Linear Birefringence in Optical Fiber Sagnac Interferometer³

As discussed in Chapter 2, the magnetic fluid possesses a large birefringence coefficient but a big transmission loss. Due to this limit, the phase difference accumulated is quite small when light passes the MF film. In this Section, we will carry out a transverse force sensor to analogize this situation to verify whether a small phase difference can work in the OFSI or not. The effects of linear birefringence in OFSI are fully investigated. Besides, the role that the birefringence plays in the OFSI is further investigated in this experiment.

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The OFSIs with various kinds of high birefringence fibers have long been used for various sensing measurement. For example, Dela Rosa demonstrated an absolute temperature sensor with a stress-induced high birefringence fiber [131]; Refractive index sensor was proposed by using D-type high birefringence fiber [120]; Chemical etching in the OFSI with a bow-tie high birefringence fiber was also demonstrated [132]. Recently, the newly emerged fiber, PCF, was also applied in the Sagnac loop [108, 117, 133, 134]. Dong demonstrated a strain sensor with polarization maintaining PCF with an ultralow temperature coefficient [108]. H.M. Kim demonstrated a transverse load sensor by employing a section of highly birefringent PCF with modified air holes on one axis and achieved the sensitivity of $\sim 2.17 \text{ nm}/(\text{N}\cdot\text{cm})$ [135]. However, there is little discussion on the OFSI by using low birefringence fiber. In this experiment, a solid core low birefringence PCF was used in the OFSI for comparison.

3.3.1 Analysis of the Effects of Transverse Force on the Fiber

There are many factors that can introduce the linear birefringence into the optical fibers. For example, in practice, the core of the optical fibers is not ideally circularly symmetric, which will cause linear birefringence to the optical fibers. The mechanical forces on the optical fibers such as strain, transverse force and bend will also cause linear birefringence. In this experiment, the transverse force is chosen as an example to introduce linear birefringence effect into the Sagnac loop.

Due to the photoelastic effect, the refractive index of fiber material will change when the optical fiber is under transverse force. The refractive indices of the optical fiber along the orthogonal directions can be given by [136, 137]

$$n_x(\lambda) = -\frac{n^3}{2E} \{ (p_{11} - 2\nu p_{12})\sigma_x + [(1-\nu)p_{12} - \nu p_{11}]\sigma_y \} \quad (3-14a)$$

$$n_y(\lambda) = -\frac{n^3}{2E} \{ (p_{11} - 2\nu p_{12})\sigma_y + [(1-\nu)p_{12} - \nu p_{11}]\sigma_x \} \quad (3-14b)$$

where $n_x(\lambda)$ and $n_y(\lambda)$ are the effective refractive indices along the two axes of the cross section of the fiber respectively; n is the initial refractive index of effective core area; p_{11} and p_{12} are the photoelastic coefficients of the fiber; E is Young's modulus of the fiber material; ν is the Poisson's coefficient of the fiber material; λ is the operating wavelength; σ_x and σ_y are the stress distributions at the effective core area, which are given by

$$\sigma_x = f/\pi R \quad (3-15a)$$

$$\sigma_y = -f/3\pi R \quad (3-15b)$$

where $f = F/L$, F is the applied transverse force; L is the contact length and R is the radius of the fiber. The birefringence of the optical fiber which is induced by the transverse force can be give by

$$B = n_y(\lambda) - n_x(\lambda) \quad (3-16)$$

By substituting Eq.(3-14a) and Eq.(3-14b), Eq.(3-16) can be given by

$$B = n_y(\lambda) - n_x(\lambda) = \frac{2n^3(1+\nu)(p_{12} - p_{11})}{E\pi RL} F \quad (3-17)$$

Eq.(3-17) shows that the birefringence (B) induced by transverse force on fiber is directly proportional to the applied transverse force (F).

3.3.2 Experimental Verification

A standard Sagnac fiber loop is shown in Figure 3-3. It was formed simply by splicing both ends of a solid core PCF (LMA-10, manufactured by NKT Photonics A/S) into the two output ports of a single mode fiber 3dB coupler. The scanning electron graph (SEM) exhibits clearly the cross section of the solid core PCF, which has a circular symmetry with core diameter $10\ \mu\text{m}$, cladding diameter $125\ \mu\text{m}$ and mode field diameter $7.5\ \mu\text{m}$ (the inset of Figure 3-3).

Figure 3-3 Schematic diagram of the experiment setup. Inset: SEM of the cross section of the PCF (LMA-10)

The PCF and the SMF coupler were spliced by using a common commercial arc fusion splicer. Because the mode field and numerical aperture of the PCF did

not match the ones of the SMF, besides, the air holes of PCF would be collapsed during the fusion splicing process, the splicing loss was larger than the one of traditional fiber. After adjusting the arc duration and arc position of the splicer, the splicing loss was lowered to be about 4dB. Lower insertion loss can be achieved by applying intermediate fiber or further optimizing the splicing parameters. However, the sensing accuracy and reproducibility of the load sensor were not affected by the relatively large splicing loss since the output of the sensor was the shift of the dip wavelength which was independent on the transmission power.

Figure 3-4 Measured transmission spectra under different mechanical loads

The light from a broadband light source (C+L band ASE source, 1520-1620nm) was split into two beams equally which counterpropagate along the loop, then recombined and interfered at the 3-dB coupler again. In the absence of birefringence in the Sagnac fiber loop, all the input light, at all wavelengths, would reflect back at the input port, and none would appear in the output port of the

perfect 3-dB coupler which was connected to the optical spectrum analyzer (OSA). The introduction of birefringence and a particular combination of input polarization would lead to a wavelength-dependence output (Figure 3-4). In order to introduce this birefringence, an initial mechanical transverse force was applied on the PCF and birefringence was generated due to photoelastic effect of the fiber. The measured mechanical load would produce an extra birefringence which would lead to the shift of the spectrum.

Taking no account of the insertion loss in the Sagnac loop, the relative transmission ratio T of the OFSI is described as (Here a modified expression of Eq.(3-10) is used)

$$T = \frac{1}{2}(1 - \cos \varphi) \quad (3-18)$$

The total phase difference $\varphi = 2\pi BL/\lambda$ is caused by the birefringence effect. Further, $BL = B_0L_0 + B_F L_F$, where B_0 is a constant which is introduced by initial transverse force over the length L_0 on the PCF including the intrinsic birefringences of PCF and SMF in the loop. B_F is induced by measured mechanical load over the length L_F on the PCF. λ is the guided wavelength.

When $\varphi = 2\pi m$ (m is an integer), T reaches its minimum. Then the wavelength spacing between two adjacent minima S can be obtained as

$$S = \frac{\lambda^2}{BL} \quad (3-19)$$

The phase difference in Eq.(3-18) changes in response of length and birefringence which are affected by mechanical load variation and temperature.

Subsequently, the spectrum shifts with temperature and transverse mechanical load are given as [135]:

$$\Delta\lambda \propto (L \frac{\partial B}{\partial T} + B \frac{\partial L}{\partial T})\Delta T + (L \frac{\partial B}{\partial F} + B \frac{\partial L}{\partial F})\Delta F \quad (3-20)$$

where ΔT is the temperature variation and ΔF is the mechanical load variation. $\partial L/\partial T$ and $\partial L/\partial F$ describe the elongations of the fiber due to the temperature and mechanical load variation, respectively. We neglect $\partial L/\partial T$ and $\partial L/\partial F$. Considering that B_0 is a constant and the ultralow thermal dependence of PCF, the final relationship between the shifts of the transmission spectrum and the transverse mechanical load is obtained as

$$\Delta\lambda \propto L_F \frac{\partial B_F}{\partial F} \Delta F \quad (3-21)$$

where $\partial B_F/\partial F$ stands for the birefringence variation coefficient introduced by the measured transverse mechanical load ΔF , which is a constant depending on the material properties including photoelastic coefficients, Young's modulus and Poisson's coefficient [136]. It is shown by Eq.(3-21) that wavelength shift $\Delta\lambda$ is directly proportional to the transverse mechanical load ΔF .

Usually, internal birefringence is created by anisotropy in the air-hole cladding in PM-PCF, such as introducing larger holes near the core in one axis [135] or creating elliptical core [138]. This anisotropy makes the birefringence properties depend on the orientation of the force applied on the PM-PCF. Different from the PM-PCF, the effective index profile of LMA-10 (non-PM PCF) can be treated as circular symmetry approximately, though this PCF has hexagonal-lattice structure

(the inset of Figure 3-3). Thus, transverse-load-induced birefringence differences caused by different fiber orientations can be ignored.

3.3.3 Experimental Results and Discussion

A metal plate was used to introduce initial linear birefringence by applying a lateral force on a section of solid core PCF as shown in Figure 3-3, which can be adjusted so that the wavelength of the dip due to interference in the transmission spectrum appeared within the range of the broadband light source (1520nm-1620nm) and the OSA (AQ6370). The supporting fiber, together with the solid core PCF, were used to keep the metal plate in a balanced condition. The line in Figure 11 indicated by “0g” shows the initial transmission spectrum with a narrow deep dip whose fringe contrast is as high as 35dB at 1567.7nm.

Several metal blocks with similar masses, which were measured with digital counting scale in advance (around 80g), were placed one by one on the load carrier whose contact length with fiber was 20mm. Subsequently, a series of curves were obtained by the OSA which are shown in Figure 3-4. The dip wavelength shifted from 1567.7nm to 1611.9nm, about 44.2nm towards the red side when the load was increased from 0g to 889.45g. The measured data of dip wavelength shifts as a function of applied mechanical load is shown in Figure 3-5. Linear fitting method was applied to the curve and a wavelength shift versus load sensitivity of 5.19nm/N was achieved with a high fitting R^2 value of 0.9959, which mean an excellent linearity. The sensitivity was 10.38nm/N since the applied mechanical load was shared by both the sensing PCF and the optical table equally.

The resolution of the sensor of 0.96mN was achieved at the limiting resolution of the OSA of 10pm. Considering the 20mm-contact length between the load carrier and the sensing PCF, the sensitivity of the sensor is 0.519 nm/(N·mm) which is better than the result of long period grating (LPG) [135, 139]; and the resolution is 0.048 mN/mm. Sensitivity and resolution can be further improved by removing the coating of the PCF [135].

Figure 3-5 Wavelength versus applied mechanical load

Temperature-dependence experiment was also conducted in a temperature-controlled oven. The wavelength of the dip at 1563nm shifted towards blue side by about 50pm with the temperature increasing from 30°C to 100°C which is shown in Figure 3-6. The temperature-dependence coefficient was 0.7pm/°C, which can be further reduced by removing the coating layer of the PCF. Considering there is a temperature drift of 10°C in the sensing environment, it is about 7pm shift in transmission spectrum which is even smaller than the resolution of the OSA. It proves that temperature effect can be neglected in Eq.(3-20).

Figure 3-6 Wavelength shift of the dip wavelength against temperature

Figure 3-4 shows that only one dip appears in the whole wavelength range from 1520nm to 1620nm and no other dip appeared when the dip shifts from the shortest wavelength to the longest wavelength. It means the period of T as described by Eq.(3-19) is well beyond 100nm, which represents the dynamic range of the proposed sensor is beyond 20N with the sensitivity of 0.519 nm/(N·mm).

3.3.4 Conclusion

In conclusion, a Sagnac fiber loop for mechanical load sensing by using a solid core PCF under external transverse force as sensing component is developed and demonstrated. Compared with the other types of optical fiber mechanical load sensors, this low birefringence PCF Sagnac loop sensor has a higher sensitivity and large measurement range for mechanical load sensing. A sensitivity of 0.519 nm/(N·mm), resolution of 0.048 mN/mm and dynamic range of 20N are achieved which are better than other types of fiber based mechanical load sensors. It is also

immune to temperature impact with a temperature dependence coefficient of $0.7\text{pm}/^{\circ}\text{C}$.

The linear birefringence plays an important role in the Sagnac interferometer. The result shows the spectral shift has a good linear relationship with the linear birefringence. With this sensor structure, intrinsic linear birefringence affects the initial dip wavelength, which can be taken account into the effect of the initial applied force. So the intrinsic linear birefringence will not have harmful effect on the sensitivity of the sensor. Meanwhile, the extra linear birefringence induced by the load (or by the magnetic fluid) provides the necessary change of the birefringence for measurement.

3.4 Effects of Circular Birefringence in Optical Fiber Sagnac Interferometer⁴

Section 3.3 shows that the linear birefringence effect can both work in the high birefringence OFSI and low birefringence OFSI. Meanwhile, the high birefringence OFSI and low birefringence OFSI have the same linear function with the variation of the birefringence effect. As discussed in Chapter 2, MF also exhibits circular birefringence effect (Faraday effect) in addition to the linear birefringence effect under external magnetic field. In this Section, we will carry out a twist sensor to analogize the circular birefringence effect in OFSI to verify whether a circular birefringence can work in the OFSI or not.

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For the sensors based on OFSI, most attentions were paid on linear birefringence caused by strain [140], core deformation [6], pressure [134] and so on. However, circular birefringence is also important and worthy for attention. Twist is one of the major causes of the circular birefringence in the fiber. Various high birefringence PCFs were used in the Sagnac loop to realize the twist sensors and obtained a linear relationship between the spectral shift and the twist angle with sensitivities of $0.06\text{nm}/^\circ$ [141] and $-0.08\text{nm}/^\circ$ [142]. Low birefringence fiber was also employed in the Sagnac loop. J.M. Estudillo-ayala analyzed the twist effect on the low birefringence fiber in the Sagnac loop [143, 144]. Y.X. Jin mentioned the twist induced spectral shift in a single mode fiber based SI was sinusoidal [145], which was different from the experimental result of the sensor based on high birefringence fiber. In this experiment, we focused on the circular birefringence effect in low birefringence OFSI. The effects of circular birefringence in high birefringence OFSI and low birefringence OFSI are also compared in this experiment.

3.4.1 Analysis of the Twist Effects on the Fiber

In a practical fiber, the core area is often not perfectly circular symmetry due to residual stress which leads to the intrinsic linear birefringence $\Delta\beta$. When the fiber is twisted, core deformation and shear strain give rise to a component of linear birefringence and circular birefringence. The total effects of the twisted fiber can be treated as a retarder and a rotator [146]. BY fixing one end of the fiber and twisting

on the other end, the retardance $\Phi_R(\theta)$ between the two orthogonal guided modes is expressed as a function of torsion angle θ which is given as [146]:

$$\Phi_R(\theta) = 2 \sin^{-1} \left(\frac{\rho}{\sqrt{1 + \rho^2}} \sin \gamma z \right) \quad (3-22)$$

where

$$\rho = \frac{\Delta\beta}{2(\theta - \alpha)} \quad (3-23)$$

$$\gamma = \sqrt{(\Delta\beta/2)^2 + (\theta - \alpha)^2} \quad (3-24)$$

z is the twisted fiber length. α is the strain induced optical rotation which is proportional to θ and given as:

$$\alpha = g\theta \quad (3-25)$$

where g is a constant which depends on the photoelastic coefficients of the material. For a single mode fiber, $g \approx 0.08$. If the center of the fiber is twisted while both ends of the fiber are fixed, the twisted effects are doubled and twice of the twist angle (2θ) is used in the equations. The simulation results are shown in Figure 3-7.

For the case of high birefringence fiber, the linear birefringence is greater than circular birefringence induced by the twist [146]. Little amount of light couples between the two polarized modes, thus the twisted fiber acts as a rotator. Then retardance $\Phi_R(\theta)$ varies linearly with the twist angle periodically in every linear region (Figure 3-7).

For the case of low birefringence fiber, the intrinsic linear birefringence is smaller than the circular birefringence [146]. The retardance $\Phi_R(\theta)$ becomes

$$\Phi_R(\theta) = \Delta\beta \frac{\sin[(\theta - \alpha)z]}{\theta - \alpha} \quad (3-26)$$

which can be described by a Sinc function ($\sin x/x$) approximately (Figure 3-7).

Figure 3-7 Calculated fiber retardance as a function of twist angle

3.4.2 Experimental Verification

The setup is similar to the one in Section 3.3. The schematic diagram of the twist sensor is shown in Figure 3-8. The configuration is based on a Sagnac interferometer which was obtained by splicing a section of 50-cm-length solid core low birefringence PCF (LMA-10, NKT Photonics A/S) with the two output ports of a 3-dB SMF coupler (Figure 3-8). The scanning electron graph (SEM) in Figure 3-8 shows a hexagonal arrangement of air-holes around the solid core in the cross section of the PCF which is approximately circular symmetric. The core, cladding, air-hole and mode field diameters are $10\ \mu\text{m}$, $125\ \mu\text{m}$, $3.04\ \mu\text{m}$ and $7.5\ \mu\text{m}$, respectively. The total splicing loss between SMF and PCF is about 4dB with a

commercial arc splicer, which can be further reduced by optimizing the parameters of splicer.

Figure 3-8 Sensing scheme based on low birefringence PCF for twist measurement
Inset: SEM image of the cross section of the PCF (LMA-10)

The 3-dB coupler splits the light into two beams counterpropagating along the loop and recombines them again. Subsequently, the two beams interfere at the 3-dB coupler. If the insertion loss in the loop is neglected, the relative transmission ratio T is given as [140]:

$$T = \frac{1}{2}(1 - \cos \Phi) \quad (3-27)$$

In the absence of birefringence in the loop, the total phase difference $\Phi = 0$, so $T=0$. All the input light of all the wavelengths would reflect back completely to the input port of the ideal 3-dB coupler and no interference fringe appears on the optical spectrum analyzer (OSA).

A transverse force is applied on the low birefringence PCF to introduce an initial linear birefringence which will lead to a constant phase difference $\Phi_0 = 2\pi BL/\lambda$, where B is the linear birefringence induced by the mechanical force over the length of L on the PCF; λ is the operating wavelength. If a broadband light source is launched, a wavelength-dependent sinusoidal interference fringe is observed (the inset in Figure 3-9). When the low birefringence PCF is twisted, the fringe will be shifted due to the extra circular birefringence and phase difference $\Phi_R(\theta)$ caused by the twist. In this case, the total phase difference can be expressed as $\Phi = \Phi_0 + \Phi_R(\theta)$. Considering Φ_0 is a constant and ultralow thermal dependence property of the PCF, the spectral shift $\Delta\lambda$ is given by

$$\Delta\lambda \propto \left(\frac{\partial\Phi_R(\theta)}{\partial\theta}\right)\Delta\theta \quad (3-28)$$

For the case of high birefringence fiber, the simulation result (Figure 3-7) and the experimental results in [141] show that, the coefficient $\partial\Phi_R(\theta)/\partial\theta$ is a constant, so $\Delta\lambda$ is linearly proportional to the twist angle θ . On the other hand, for the case of low birefringence fiber, $\Delta\lambda$ is following a pattern of Sinc function.

The sensitivity of the sensor depends on the coefficient $\partial\Phi_R(\theta)/\partial\theta$. Thus the use of the low birefringence PCF is one of the best choices for the proposed sensor to improve the twist sensitivity. It is because of its air-hole structure, the sensor based on PCF is more sensitive to fiber twist effects than traditional fiber [141, 142]. Moreover, if the HBF is used for this proposed sensing scheme, the circular birefringence caused by the twist effects will be greatly swamped by the larger linear birefringence of HBF itself [146]; hence the twist sensor based on low

birefringence fiber will achieve a higher twist sensitivity than the one based on high birefringence fiber. Finally, the ultralow thermal dependence property of the PCF will decrease the influence of the ambient temperature variation and increase the twist sensitivity.

3.4.3 Experimental Results and Discussion

A length of 20-mm PCF, together with a balanced fiber, was clamped between two metal plates in order to introduce the necessary initial birefringence. The force applying on the PCF was adjusted until the dip of the transmission spectrum appeared on the OSA (AQ6370) within the range of the amplified spontaneous emission (ASE, 1520-1620nm) light source. The curve indicated by “0°” in Figure 3-9 shows the initial transmission spectrum with the wavelength of the dip at 1578.1nm.

Figure 3-9 Variation trend of measured transmission spectra at different twist angles
 Inset: measured transmission spectra at twist angles of 0° and 60°

When the PCF was twisted from its center clockwise (CW) or counterclockwise (CCW), the transmission spectrum shifted to the shorter or longer wavelength side, respectively, which was completely reversible and repeatable. The inset in Figure 3-9 shows the measured transmission spectra at the twist angles of 0° and 60° . In order to obtain the twist sensitivity of the sensor, the transmission spectra were recorded by increasing the twist angle from 0° to 360° with an interval of 10° . It shows the dip wavelength shifts periodically and the variation trend is similar to Sinc function by the 3D image in Figure 3-9.

The visibility of the transmission spectrum varies totally about 10dB during the process of applied twist effect. The reason is that the splitting ratio of the coupler depends on the wavelength and polarization state [147], so the actual splitting ratio slightly deviates from 3dB, which caused the decrease in the visibility of the interference fringes. Moreover, the change of the dip wavelength in the spectrum of the proposed sensor is used to measure the twist effect, so the performance of the sensor is not affected by the variation on the visibility of the transmission spectrum.

The relationship between the dip wavelengths and the twist angles is shown in Figure 3-10. The dip wavelength shifted 52.7nm from the minimum wavelength 1545.2nm at the twist angle of 60° to the maximum wavelength 1597.9nm at the twist angle of 140° during the first period, which is 3 times larger than the shift range of the sensor employing SMF [145]. Comparing the results of the sensor based on PCF and SMF, the variation trends were similar, but PCF were more sensitive to the twist effect [145]. The curve was fit with a Sinc function by a high

R^2 value of 0.9898, which means the experimental data was in accordance with the simulation results.

Figure 3-10 Dip wavelength shift with the twist angle

Taking the linear range from 75° to 140° as an example, linear fit was applied to the curve by a high R^2 value of 0.9937, which means the dip wavelength increased with a good linearity. The sensitivity in this linear region is $1.00\text{nm}/^\circ$. In practical application, the sensor can be pretwisted to this linear range for achieving a high sensitivity. This achieved sensitivity of the proposed twist sensor is 17 times and 12.5 times higher than that of the twist sensor by use of high birefringence PCF [141] and PM-side hole fiber [142] based OFSI, respectively, 521 times higher than that of the polarization mode interferometer by means of fabrication two in-line polarizers on the hollow core PCF [148], 255 times higher than that of ultra long-period LPG [149]. The sensitivity is greatly enhanced. The resolution of the sensor was 0.01° at the limiting resolution of the OSA of 10pm .

Another distinct advantage of the twist sensor based on PCF is the ultralow temperature sensitivity, which was confirmed experimentally. Figure 3-11 shows the dip wavelength moved about 40pm to short wavelength side when the temperature increased from 30°C to 100°C. The temperature coefficient is -0.5pm/°C which can be neglected comparing to the high twist sensitivity of 1nm/°.

Figure 3-11 Dip wavelength shift at different temperatures

3.4.4 Conclusion

A twist sensor employing a section of low birefringence PCF inserted in the OFSI is proposed and experimentally demonstrated with an enhanced sensitivity. The sensor has a sinusoidal wavelength-dependence output with the assistance of the initial mechanical transverse force applied on the low birefringence PCF which is used for introducing initial necessary constant linear birefringence. The transmission spectral shift is a Sinc function form which is different from the result of the twist sensor by employing high birefringence fiber. The sensor achieved a largely enhanced sensitivity of 1.00nm/° and a high resolution of 0.01° with a good

repeatability. The temperature-insensitive property was conformed experimentally with an ultralow temperature coefficient of $-0.5\text{pm}/^{\circ}\text{C}$.

Twist effects on high birefringence PCF and low birefringence PCF were theoretically analyzed which were in accordance with the experimental results reported. The relationship between the spectral shift and the twist angle is following a linear relationship. The reason is that the intrinsic linear birefringence is much larger than the circular birefringence caused by the twist. Subsequently, the twist effect is unable to couple any significant amount of light from one polarization mode to the other polarization mode in the existence of the high linear birefringence of the polarization maintaining fiber. Hence the effect of the circular birefringence is swamped effectively.

The relationship between the spectral shift and the twist angle of low birefringence fiber is following a Sinc function. The reason is that the intrinsic linear birefringence is comparable to the circular birefringence induced by the twist of the fiber. Coupling of light occurs between the two guided modes along two polarized modes periodically.

As for the application of MF in OFSI, circular birefringence induced by magnetic field is very small. If the circular birefringence is used in a high birefringence OFSI, it may be swamped by the high linear birefringence of the high birefringence fiber. If the circular birefringence is used in a low birefringence OFSI, it will be a Sinc function relationship with birefringence change. Once the configuration is fixed, we should leave the fiber as it is and avoid twisting the fiber during the process of measurement. Then, any circular birefringence exists in the fiber can be taken as a constant, which will not affect the measurement result.

3.5 Chapter Summary

First, we briefly review the flexible applications of OFSIs in this Chapter and attention is focused on the sensing applications. Theoretical analysis based on Jones Matrix is carried out and the expressions of the characteristic parameters of OFSI such as transmission spectrum, period and sensitivity are obtained. Hence, further investigations on the OFSIs can be deduced on the basis of this series of formulas.

As discussed in Chapter 2, MF has both the linear birefringence effect and the circular birefringence effect (Faraday effect). The OFSI can be served as a platform for demodulating both the linear birefringence effect and the circular birefringence effect of MF. As for the effects of linear birefringence of MF in OFSI, a transverse force sensor is carried out to analogize the situation. The spectral shift (dip wavelength shift) shows a good linear relationship with the birefringence change no matter in a high birefringence OFSI or a low birefringence OFSI. As for the effects of circular birefringence of MF, a twist sensor is carried out to analogize the situation. The spectral shift (dip wavelength shift) shows a Sinc function relationship with the birefringence change in a low birefringence OFSI but a linear relationship with the birefringence change in a high birefringence OFSI. However, the sensitivity to the circular birefringence in the low birefringence OFSI is higher than the one in the high birefringence OFSI. In other words, the relative small circular birefringence may be swamped by the relative high linear birefringence in the circular birefringence.

The MF has a large transmission loss. The typical thickness of MF film is just as thin as several tens of microns. The effects of birefringence cannot be accumulated through increasing the propagation length in the MF film. Therefore, considering the practical parameters of MF and above conclusions obtained in these Sections, we highly recommend using the linear birefringence of MF in the OFSI for sensing applications. The linear birefringence of MF can work in both the high birefringence OFSI and the low birefringence OFSI, but the measurement sensitivity of low birefringence OFSI configuration is better.

In this Chapter, only the proposed method of applying OFSI as the demodulation scheme for the birefringence effects are demonstrated. Further issues on the performance of the MF-based devices such as dichroism effect, sensitivity, fringe contrast, etc will be discussed in the following Chapters.

Chapter 4 Development of the Fiber Optics Applications by Using Birefringence Property of Magnetic Fluid

4.1 Introduction^{5,6}

Magneto-optical sensors and other magneto-optical devices are characterized for their high resolution, ultimate precision, small size and low cost [71]. In these magneto-optical applications, magneto-optical materials are the crucial components which interact directly or indirectly with the light field and “translate” the variation of the external magnetic field into the corresponding variation of the light parameters such as intensity, phase, polarization state and so on. As reviewed in Section 2.1, MF is such a promising functional material that possesses diverse magneto-optical properties including refractive index tunability [11, 12], linear birefringence effect [13, 14], linear dichroism effect [15, 16], Faraday effect [17, 18], field dependent transmission property [19, 20], thermal lens

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effect [23, 24] and so on. Taking advantage of these magneto-optical properties, a lot of MF-based photonic devices, especially optical fiber devices, were reported including sensors, switches, modulators, filters and so on [61, 115, 150-152]. For example, by using the tunable refractive index property of MF, Hu proposed a current sensor with Fabry-Perot interferometer and achieved a sensitivity of 1.25pm/Oe [115]; Dai implemented a magnetic field sensor with etched fiber Bragg grating (FBG) with a sensitivity of 0.344pm/Oe [153]; Liu realized a tunable filter with long period grating (LPG) with a sensitivity of 4.3pm/Oe [152]; Horng demonstrated a modulator by applying MF as the cladding of an etched fiber [61]. Besides, optical switch was achieved by using the field dependent transmission property of MF [150]. Current sensor was also carried out by using the thermal lens effect of MF [23]. Among these applications, most were based on the evanescent field interacting with the tunable refractive index of MF. As well known, a significant challenge for improving the performance of evanescent-field-based optical devices is how to increase the overlap of the light field with the sensitive material. As reviewed in Section 2, in addition to the tunable refractive index property, birefringence effect of MF is another important property which was intensively investigated [15, 63], but few applications were reported. The main challenge was that the thickness of MF film is quite small which cannot be increased significantly due to the huge absorption coefficient of MF, subsequently the phase difference caused by birefringence effect of MF is too small to be detected. As discussed in Chapter 2 and Chapter 3, OFSI is a better choice as a flexible tool for detecting the small phase difference caused by MF film. On the one hand, the two light beams for interference in OFSI propagate along exactly the same

optical path and experience the same absorption loss, so there is no need to balance the intensities of the two beams for interference like MZI or MI. Therefore, the challenge of the huge absorption loss of MF can be overcome by optical fiber Sagnac interferometric configuration. On the other hand, the OFSI can magnify a small phase difference caused by the MF film through some flexible designs. Therefore, optical fiber Sagnac interferometric configuration is an excellent solution for the use of the birefringence effect of MF in fiber optics applications. In this Chapter, we will verify the above ideas. Magneto-optical sensors and magneto-optical modulators are developed based on the birefringence effect of MF and their performances are improved. Then, theoretical analysis is carried out to enhance the sensitivity of OFSI-based sensors. The predictions drawn from the theoretical analysis are verified by strain sensing experiments. Finally, a phenomenon of laser self-induced tunable birefringence effect is observed with the polarimetric configuration.

4.2 Development of a Magnetic Field Sensor Based on Optical Fiber Sagnac Interferometric Configuration⁷

This work is based on the work in Section 3.4, but the initial transverse force in the setup is replaced by a section of high birefringence fiber while the variable

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transverse force (load) is replaced by a MF film. Considering that MF has linear dichroism effect in addition to the linear birefringence effect, the expression for the relative transmittance is derived and its physical meaning is explained in this work.

4.2.1 Principle of the Sensing Configuration

The sensor structure is based on an optical fiber Sagnac interferometric configuration (Figure 4-1). A MF film whose plane is perpendicular to the light propagation direction, together with a 3dB single mode fiber (SMF) coupler and a section of 50-cm-length polarization maintaining fiber (PMF) is incorporated in the loop by means of two collimators. When the magnetic field direction is perpendicular to the light propagation direction (perpendicular case), the birefringence effect and dichroism effect in MF are dominant. When the magnetic field direction is parallel to the light propagation direction (parallel case), MF mainly shows its Faraday effect. These properties play different roles in the proposed sensor. The magnetic field is generated by an electromagnet and calibrated by a gaussmeter. Light from an amplified spontaneous emission (ASE) source is split by the coupler. The two beams counterpropagate in the loop and interfere when they meet at the coupler again. The spectra of the sensor are measured by an optical spectrum analyzer (OSA).

As passing through the birefringent MF film, light is decomposed into the ordinary ray (o-ray, whose electrical field vector is perpendicular to the magnetic field direction) and extraordinary ray (e-ray, whose electrical vector is parallel to the magnetic field direction) and a phase difference is introduced between the e-ray and o-ray due to the birefringence effect of MF film. Meanwhile, the e-ray and o-

ray are absorbed with different absorption coefficients due to the dichroism effect of MF. Hence, the Jones matrix of the MF film is given by,

$$J = e^{-\frac{\alpha_o + \alpha_e}{2}d} \begin{pmatrix} e^{i\varphi_m/2 + \alpha d} & 0 \\ 0 & e^{-i\varphi_m/2 + \alpha d} \end{pmatrix} \quad (4-1)$$

where α_e and α_o are the absorption coefficients for the e-ray and o-ray, respectively; $\alpha = (\alpha_e - \alpha_o)/2$; d is the thickness of the MF film. $\varphi_m = 2\pi B_m d / \lambda$ is the phase difference caused by the birefringence (B_m) of the MF and λ is the operating wavelength.

Figure 4-1 Configuration of the magnetic field sensor based on MF film and OFSI

By using the same analysis method in Section 3.2 and Ref. [129, 130], the Jones Matrices of the Sagnac loop for the clockwise (CW) and counterclockwise (CCW) are given by

$$J_{CW} = e^{-\frac{\alpha_o + \alpha_e}{2}d} \cdot \begin{bmatrix} \cos \theta_3 & -\sin \theta_3 \\ \sin \theta_3 & \cos \theta_3 \end{bmatrix} \cdot \begin{pmatrix} e^{i\varphi_m + \alpha d} & 0 \\ 0 & e^{-(i\varphi_m + \alpha d)} \end{pmatrix} \cdot \begin{bmatrix} \cos \theta_2 & -\sin \theta_2 \\ \sin \theta_2 & \cos \theta_2 \end{bmatrix} \cdot \begin{pmatrix} e^{i\varphi_p} & 0 \\ 0 & e^{-i\varphi_p} \end{pmatrix} \cdot \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 \\ \sin \theta_1 & \cos \theta_1 \end{bmatrix} \quad (4-2a)$$

$$J_{CW} = e^{-\frac{\alpha_o + \alpha_e}{2}d} \cdot \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 \\ \sin \theta_1 & \cos \theta_1 \end{bmatrix} \cdot \begin{pmatrix} e^{i\varphi_p} & 0 \\ 0 & e^{-i\varphi_p} \end{pmatrix} \cdot \begin{bmatrix} \cos \theta_2 & \sin \theta_2 \\ -\sin \theta_2 & \cos \theta_2 \end{bmatrix} \cdot \begin{pmatrix} e^{i\varphi_m + \alpha d} & 0 \\ 0 & e^{-(i\varphi_m + \alpha d)} \end{pmatrix} \cdot \begin{bmatrix} \cos \theta_1 & \sin \theta_1 \\ -\sin \theta_1 & \cos \theta_1 \end{bmatrix} \quad (4-2b)$$

where $\varphi_p = \pi B_p L / \lambda$ is the phase difference caused by the PMF. θ_1, θ_2 and θ_3 are defined the same as the Ref. [130]. The difference is that a term $e^{\alpha d}$ appears in the equations which denotes the attenuation caused by the dichroism effect of the MF film. So the transmission function T becomes

$$T = \exp[-(\alpha_o + \alpha_e)d] \{ 2 \cos^2 \theta_2 \sin^2(\theta_1 + \theta_3) [\cosh(2\alpha d) + \cos 2(\varphi_p + \varphi_m)] \\ + 2 \sin^2 \theta_2 \cos^2(\theta_1 + \theta_3) [\cosh(2\alpha d) + \cos 2(\varphi_p - \varphi_m)] \\ + \sin 2\theta_2 \sin 2(\theta_1 + \theta_3) [\cos(2\varphi_m) + \cos(2\varphi_p) \cosh(2\alpha d)] \} \quad (4-3)$$

If the dichroism is absent, $\alpha = 0$, then $\cosh(2\alpha d) = 1$, Eq.(4-3) becomes

$$T = 4[\sin(\theta_1 + \theta_3) \cos \theta_2 \cos(\varphi_p + \varphi_m) + \cos(\theta_1 + \theta_3) \sin \theta_2 \cos(\varphi_p - \varphi_m)]^2 \quad (4-4)$$

Eq.(4-4) is the same as the result in Ref. [130] which commonly appears in the literatures.

If the fast axis of the PMF is parallel to the fast axis of the magnetic fluid, $\theta_2 = 0$, Eq.(4-3) becomes

$$T = 2 \exp[-(\alpha_o + \alpha_e)d] \sin^2(\theta_1 + \theta_3) [\cosh(2\alpha d) + \cos 2(\varphi_p + \varphi_m)] \quad (4-5)$$

Then, the total difference (φ) caused by the birefringence of the MF and PMF gets its maximum, ie. $\varphi = \varphi_p + \varphi_m$.

If the fast axis of the PMF is parallel to the slow axis of the magnetic fluid,
 $\theta_2 = \pi/2$, Eq.(4-3) becomes

$$T = 2 \exp[-(\alpha_o + \alpha_e)d] \cos^2(\theta_1 + \theta_3) [\cosh(2\alpha d) + \cos 2(\varphi_p - \varphi_M)] \quad (4-6)$$

Then, the total phase difference (φ) caused by the birefringence of the MF and PMF gets its minimum, ie. $\varphi_{\max} = \varphi_p - \varphi_M$.

Often the case, the birefringence axes of the PMF are not aligned with the axes of the MF, then the total phase difference (φ) is between the maximum ($\varphi_{\max} = \varphi_p - \varphi_M$) and the minimum ($\varphi_{\min} = \varphi_p - \varphi_M$).

Because the attenuation item $e^{\alpha d}$ is added, the final expression Eq.(4-3) becomes very complicated and we cannot infer directly how the birefringence effect and dichroism effect affect the transmission spectrum of the sensor. In order to explain the experimental results clearly, the modified equation is used here

$$T = 2 \exp[-(\alpha_o + \alpha_e)d] \cos^2(\theta_1 + \theta_3) [\cosh(2\alpha d) + \cos 2\varphi] \quad (4-7)$$

where the value of φ is between $\varphi_{\max}$ and $\varphi_{\min}$.

Eq.(4-7) shows T is an approximately sinusoidal function of wavelength λ (Figure 4-2). The dip wavelength of the transmission spectrum depends on the total phase difference (φ), which further depends on the birefringence of the MF (B_m). B_m is dependent on the external magnetic field strength. Therefore, the magnetic field strength can be measured by monitoring the dip wavelength of the transmission spectrum. The period S is inversely proportional to φ . If φ is very small, S will be too large and exceed the spectrum range of the light source. On the contrary, if φ is too large, S will be too small which means a small dynamic

measurement range. In this proposed sensor, since the thickness of MF film is so small (tens of microns) that only MF film itself cannot generate φ in an appropriate range for measurement, so a 50-cm-length PMF is inserted into the Sagnac loop to provide an initial constant phase difference for offset purpose. The fringe contrast of T is dependent on the terms of $e^{-(\alpha_o + \alpha_c)d}$ and $\sin^2(\theta_1 + \theta_2)$. For the perpendicular case, both birefringence and dichroism effects need to be considered, while Faraday effect is ignored, so the dip wavelength of the spectrum will shift with the variation of the applied magnetic field strength. For the parallel case, Faraday effect is considered, while birefringence and dichroism effects are ignored, but the relative small circular birefringence caused by Faraday effect will be swamped by the relative large linear birefringence of PMF, so the spectrum will not shift with the variation of the applied magnetic field strength.

Figure 4-2 Output spectrum of the proposed sensor

4.2.2 Experimental Results and Discussion

The MF used in the experiment (EMG605, Ferrotec) is a water-based ferrofluid which is fabricated by the chemical coprecipitation technique. It is a black-brown

translucent liquid [71]. The nominal diameter of the nanoparticles, Fe_3O_4 , was 10nm. The volume concentration is 3.9%. The magnetic susceptibility and saturation magnetization are 2.96 Gs/Oe and 220 Oe, respectively. The MF was sealed between two $10 \times 10 \text{ mm}^2$ optical glasses with UV glue to form thin MF film. Three samples of different thicknesses (20, 30 and $60 \mu\text{m}$) were prepared.

For the perpendicular case, a series of spectra were recorded in Figure 4-3 as the magnetic field strength was increased. The initial transmission spectrum under zero magnetic field is indicated by “6.1 Oe” with its dip wavelength at 1563.18nm and its fringe contrast is about 30dB. As the magnetic field strength was increased from 0Oe to 2013Oe, the dip wavelength shifted to the longer wavelength side from 1563.18nm to 1564.99nm and the corresponding fringe contrast decreased 15dB. The decrease of the fringe contrast was caused by the dichroism effect of the MF film.

Figure 4-3 Measured spectra under different magnetic field strengths for the perpendicular case

For the parallel case, a series of spectra were recorded in Figure 4-4 when the magnetic field strength was increased. As the magnetic field strength was increased from 0Oe to 2167Oe, the transmission spectrum was almost unchanged. Thus, the dip wavelength and fringe contrast of the transmission spectrum remained almost the same for different magnetic field strengths.

Figure 4-4 Measured spectra under different magnetic field strengths for the parallel case

In order to analyze the influence of different MF film thicknesses on the performance of the sensor, the experiments for the perpendicular case were repeated for the other two samples (20 & 60 μ m). The relationships between the dip wavelengths and the magnetic field strengths were recorded in Figure4-5. For the perpendicular case, when the magnetic field strength was smaller than 300Oe, the dip wavelength shifted quickly and linearly as the magnetic field strength increasing. When the magnetic field strength was larger than 400Oe, the dip wavelength shift was gradually saturated. The data can be fit well by the modified Langevin function. For the case of small magnetic field strength,

linear fit was applied. For the MF films of 20 μm , 30 μm and 60 μm , the corresponding sensitivities are 6.4pm/Oe, 11.4pm/Oe and 16.7pm/Oe, respectively and the corresponding resolutions are 1.56Oe, 0.88Oe and 0.60Oe, respectively, at the resolution limit of 10pm of the OSA. For the MF film of 60 μm , its sensitivity is about one order of magnitude better than the result of the current sensor based on FPI [115] and the result of the filter based on LPG [152], two orders of magnitude better than the result of the magnetic field sensor based on etched FBG [153]. Figure 4-5 shows the linear range of the proposed sensor for different thicknesses of MF films are the same, about 300Oe, which depends on the properties of the MF such as concentration. The dynamic range is independent on the thickness of MF film, but can be enhanced by increasing the concentration of the MF. Rapidly increasing and decreasing the magnetic field strength, the data in Figure 4-5 almost coincide, which means the sensor has a good reversibility. For the parallel case, the dip wavelength was almost unchanged. Comparing with the perpendicular case, the sensitivity is estimated to be -9×10^{-4} pm/Oe, which can be neglected.

Figure 4-5 Dip wavelength of the transmission spectrum varies with the external magnetic field strength for perpendicular case and parallel case

A tunable laser source (TLS) and an optical powermeter were used to test the sensor for benefiting dynamic sensing applications. In order to obtain the best sensitivity, the output wavelength of the TLS was tuned to one of the dip wavelengths under zero magnetic field (e.g. 1563.18nm in Figure 4-3). Hence, as the applied magnetic field strength changes, the corresponding output power will change accordingly. The normalized transmission power is shown in Figure 4-6. For perpendicular case, the data can be fit well by modified Langevin function by a high R^2 value of 0.995. The sensitivity was estimated to be 0.3998dB/Oe. The repeatability was verified, too. For the parallel case, the output power was not as stable as the measurement of the dip wavelength. The sensitivity was 0.0017dB/Oe, which was 235 times smaller than the one of the perpendicular case. The time response property of the sensor is mainly determined by the response time of the MF, which was reported in the range of 10-30ms [61]. Therefore, the highest frequency of the dynamic magnetic field the sensor can measure is about 100Hz.

Figure 4-6 Normalized transmission power varies with external magnetic field strength for perpendicular case and parallel case

4.2.3 Conclusion

In conclusion, the magnetic field sensor based on the birefringence effect of the MF film is demonstrated. The performance of the sensor is related to the magnetic field direction, so the sensor is performed in the perpendicular case and the parallel case, respectively. For the perpendicular case, the dip wavelength of the output spectrum shifts with the change of the applied magnetic field strength. The results show the thicker the MF film, the higher the sensitivity and the resolution. The best sensitivity and resolution achieved for the 60- μm -thickness MF film are 16.7pm/Oe and 0.60Oe, respectively. The sensor can also be operated as a dynamic magnetic field sensor in the frequency response range about 100 Hz with a sensitivity of 0.3998dB/Oe. The proposed sensor shows a good reversibility. On the other hand, both the dip wavelength and the output intensity almost remain unchanged with the variation of the applied magnetic field strength for the parallel case.

The proposed structure of the magnetic field sensor also has some potential applications such as modulators and switches. In the next Section, we will discuss the magneto-optical modulator based on this proposed optical fiber Sagnac interferometric configuration.

4.3 Development of Magneto-Optical Modulator

Based on Optical Fiber Sagnac Interferometric Configuration⁸

In the literatures, many MF-based photonic devices for characterization of magnetic modulation, especially optical fiber devices, have been developed. H.E. Hrong demonstrated a magneto-optical modulator by employing MF as a cladding layer with tunable refractive index [61, 151]. The achieved extinction ratio was 4% which is quite small. The multimode fiber (MMF) was used in the experiment and limited its applications in single mode fiber (SMF) system. Besides, the refractive index of MF was affected by the carrier, concentration and temperature, which should be accurately controlled. Configuration of free-space Mach-Zehnder interferometer (MZI), which made use of the tunable refractive index property of MF films, was proposed to realize a modulator and improve the extinction ratio slightly [154]. Optical fiber based MZI and cascaded modulators by utilizing MF were also demonstrated to realize optical logical operations with a further improved extinction ratio of 20% [155]. Additionally, magneto-optical modulator, which acted as an optical switch, was implemented by means of the field-dependent transmission property of MF [150].

In Section 4.2, the proposed magnetic field sensor based on the birefringence effect of MF and optical fiber Sagnac interferometric configuration is demonstrated. This

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proposed sensor is for static magnetic field application. In this Section, we will further explore the possibility of this proposed configuration for dynamic magnetic field application. A magneto-optical modulator is demonstrated in this Section. One of the distinguished features is its high extinction ratio.

4.3.1 Principle of the Modulator Configuration

The configuration and principle of the proposed magneto-optical modulator is the same as the ones in Section 4.2, but the broadband light source is replaced by a narrowband tunable laser source and the OSA is replaced by a photodetector (PD) for dynamic measurement. The light of a single wavelength from the tunable laser source (TLS) is launched into the input port of a 3dB coupler via an optical fiber isolator and is split into two light beams which counterpropagate along the Sagnac loop. Interference occurs when the two counterpropagating beams recombine at the 3dB coupler. The interference depends on the total phase difference between the two orthogonal modes, which further depends on the birefringence of the MF film and the polarization maintaining fiber. The phase difference induced by the polarization maintaining fiber is fixed whilst the phase difference induced by the MF is variable with the external magnetic field. Therefore, the light intensity modulation can be realized by modulating the external magnetic field.

The principle of the light modulation through this proposed magneto-optical modulator is shown in Figure 4-8. The curve indicated by “0Oe” is the output transmission spectrum of the modulator at zero magnetic field. The transmission power at the dip wavelength (e.g. 1551.7nm) is about -80dBm. As the increase of the magnetic field strength, the transmission spectrum shifts to the longer

wavelength side, meanwhile the fringe contrast of the transmission spectrum decreases. The transmission power at the original dip wavelength (i.e. 1551.7nm) is about -55dBm. Therefore, there is a power variation of about 25dB (indicated by ΔT in Figure 4-8) induced by the spectral shift and the decline of the fringe contrast which provides an opportunity for light modulation at certain single wavelength. The best extinction ratio of the light modulation is obtained at the dips of the transmission spectrum.

Figure 4-7 Scheme of magneto-optical modulator based on OFSI. 1&2: collimator; 3: magnetic fluid film; 4: electromagnet.

4.3.2 Experimental Results and Discussion

A water-based MF (EMG605, Ferrotec), which contained ferrite nanoparticles, Fe_3O_4 , with a nominal particle diameter of 10nm and magnetic nanoparticle concentration of 3.9%, was injected in a 22mm×22mm glass cell with a thickness of 50 μm and sealed with UV glue to form a MF film. The MF film was placed between a pair of optical fiber collimators with its plane normal to the light direction and parallel to the magnetic field direction (Figure 4-7). The magnetic field was supplied by an electromagnet (EM4-HVA, LakeShore) which was

programmable and measured with a gaussmeter (Model 425, LakeShore). The section of a 50-cm length PMF with birefringence of 3.3×10^{-4} (PMF, PM-1550-HP, Thorlabs) was used in the OFSI. The broadband coupler, polarization insensitive isolator and collimators were all operated at the central wavelength of 1550nm.

Firstly, a C+L band amplified spontaneous emission (ASE, 1520-1610nm) light source and optical spectrum analyzer (OSA, AQ6370) were employed to measure the sinusoidal interference transmission spectra under external magnetic fields at 23.7°C (Figure 4-8). The curve indicated by “0Oe” is the transmission spectrum under zero magnetic field, whose period is 11.2nm. With the magnetic field strength increasing from 0Oe to 2000Oe, the transmission dip around 1550nm, which was taken as an example, shifted to the longer wavelength side from 1551.7nm to 1553.3nm, as well as the fringe contrast (visibility) of the spectra decreased from 34dB to 14dB. The spectrum shifted rapidly and linearly when the

magnetic field strength was smaller than 180 Oe. With the magnetic field strength increasing further, the spectral shift tended to saturate gradually. It means a small magnetic field strength is enough for modulation, for example 50Oe, which makes a high speed modulation feasible.

Figure 4-9 Output intensity of the modulator versus the external magnetic field

Then, a tunable laser source (TLS, AQ8203) and a photodiode (HRPD-2841A) were employed to realize an intensity modulator. The extinction ratio is dependent on the variation of the transmission intensity with the external magnetic field at a certain wavelength of the TLS. In order to obtain the best extinction ratio which is about 25dB denoted by ΔT as shown in Figure 4-8, the wavelength of the TLS was set to be equal to the transmission dip wavelength of the OFSI under zero magnetic field, saying 1551.7nm. The input intensity was 1mw. The output intensity changed with the rapid variation of external magnetic field which was tended to be saturate at a larger magnetic field strength, too (Figure 4-9). The intensity was measured when the magnetic field strength was rapidly increased and

decreased (Figure 4-9). The results show a good repeatability which indicate that, as well known, there is no hysteresis effect in MF. Langevin function was used to fit the data by a high R^2 value of 0.995 [156].

To demonstrate this magneto-optical modulator, square-wave and sinusoidal-wave modulations of the magnetic field strength were applied on the MF film and the corresponding optical outputs were recorded which are shown in Figure 4-10. The amplitudes of magnetic field strength for the square-wave and sinusoidal-wave modulation were set at 180 Oe and 100 Oe, respectively, while the corresponding extinction ratio were 19.5dB and 18.3dB, respectively, which can be further improved to about 25dB by applying a stronger magnetic field according to the results in Figure 4-8 at the cost of reducing the modulation frequency.

The frequency response of the proposed modulator is dominated by the response time of the ferromagnetic nanoparticles in MF, which depends on the concentration of the MF and external magnetic field strength. The response time are measured in the literatures, whose typical value ranges from 10-30ms [14, 61, 155], so the highest modulation frequency is around 100Hz. This modulator may not work in the high modulation frequency applications in optical communication systems, but it is good enough for applications such as switch, routers, display and so on [61].

4.3.3 Conclusion

In conclusion, the magneto-optical modulator based on the optical fiber Sagnac interferometric configuration is feasible, in which MF acts as a magnetically sensitive material offers magnetically controlled birefringence effect. The experimental data on the transmission intensity of the modulator were fit well by Langevin function and showed a good repeatability. Magnetic fields, which were modulated as square and sinusoidal forms, were applied on the modulator with a high extinction ratio of 19.5dB and 18.3dB, respectively, which can be further improved by raising strength of magnetic field at cost of reducing the modulation frequency. Finally, the proposed setup of the modulator is much simpler and has the potential to be developed into an integrated optical fiber device.

In this experiment, we found that if some conditions were fulfilled, the extinction ratio of the modulator could be improved further. In the next Section, we will devote efforts to improve the extinction ratio of the modulator.

4.4 Development of a Magneto-Optical Modulator Based on Polarimetric Configuration⁹

Among the various MF-based applications, magneto-optical modulators or switches were most intensively investigated and heavily reported [19, 62, 72, 73, 150, 151, 157-163]. One of the efforts is devoted to improve the extinction ratio (ER) of the modulator, which is defined as the ratio of maximum to minimum of the optical transmission power when it is operated as ON-state and OFF-state, respectively.

The reported MF-based magneto-optical modulators can be further classified into two classes according to the modulation methods: intensity-modulation type and phase-modulation type. In the intensity-modulation-type modulators, the light intensity is absorbed by the MF or attenuated by the MF-assisted fiber directly. The field dependent transmission property of the MF is responsible for the absorption of the light, which was applied to realize light modulation with extinction ratio of 0.8dB [158]. Higher ER up to 10dB can be achieved by increasing the thickness of MF film at the cost of reducing modulation speed to hundreds of seconds [164]. Besides, MF-assisted fiber modulators were carried out by utilizing the MF as the refractive-index tunable cladding of an etched multimode fiber (MMF) [151] or a tapered single mode fiber (SMF) [159] with ERs of 0.5-0.9dB. The refractive index of the MF, which is susceptible to temperature, should be carefully selected and controlled. In the phase-modulation-

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type modulators, various optical interferometers are employed to convert the phase difference, which is induced by the magneto-optical effects of MF, to light intensity modulation indirectly. A Fabry-Perot interferometer (FPI) by utilizing the refractive index tunability of MF was reported as a tunable wavelength filter [115]. Fiber Mach-Zehnder interferometer (MZI) was demonstrated for optical signal processing with an ER of 0.55dB [155]. In Section 4.3, we demonstrated an OFSI-based modulator with the MF film inserted into the fiber loop with a greatly improved ER of 19.5dB [62]. Through some further analysis on the result in Section 4.4, we figure out the factors that affect the ER of the modulator and then propose a modulator based on the polarimetric configuration. In this Section, we demonstrate the modulator based on the polarimetric configuration with an improved ER of 38dB.

4.4.1 Principle of the Modulator Configuration

The structure of the proposed modulator is shown in Figure 4-11. The plane of the MF film is normal to the light propagation direction and parallel to the external magnetic field direction. The collimated light, which is linearly polarized after passing through the polarizer (P_1), is decomposed into two orthogonal linearly polarized beams when traveling in the MF film as well as the polarization maintaining fiber (PMF). The e-ray and o-ray propagate at different speeds due to the birefringence effects of the MF film as well as the PMF and experience different absorption losses due to the dichroism effect of the MF film. Subsequently, the components of e-ray and o-ray on the direction of the analyzer (P_2) interfere and a wavelength dependent interference spectrum is observed at the analyzer (P_2).

Figure 4-11 Schematic diagram of the modulator based on polarimeter

In the configuration, the slow axis of the MF film (parallel to the magnetic field direction) is configured to be parallel to the fast axis of the PMF. So, the total phase difference is given as $\varphi = \varphi_{PM} - \varphi_{MF}$, where $\varphi_{PM} = 2\pi B_{PM} L / \lambda$ is the phase difference caused by the birefringence of PMF (B_{PM}) over the fiber length (L); $\varphi_{MF} = 2\pi B_{MF} d / \lambda$ is the phase difference caused by the birefringence of MF film (B_{MF}) over the thickness of (d); λ is the operating wavelength. φ_{PM} is a constant, while φ_{MF} is a variable with the external magnetic field strength.

The linearly polarized light after P_1 is decomposed into two components along the slow axis and fast axis of the MF film which can be given as $E_0 \cos \alpha$ and $E_0 \sin \alpha$, respectively. E_0 is the amplitude of the electrical vector of the linear polarized light after P_1 ; α is the angle between P_1 direction and magnetic field direction X . After the MF film and the PMF, the two components become $E_0 \cos \alpha \cdot e^{-\alpha_e d}$ and $E_0 \sin \alpha \cdot e^{-\alpha_o d} e^{-i\varphi}$ for the X and Y direction, respectively. α_e and α_o are the according absorption coefficients for the two components, respectively. Subsequently, the two light components project on the P_2 direction again and become

$$E_1 = E_0 \cos \alpha \cdot e^{-\alpha_e d} \cdot \cos(\alpha + \beta) \quad (4-8a)$$

and

$$E_2 = E_0 \sin \alpha \cdot e^{-\alpha_o d} e^{-i\varphi} \cdot \sin(\alpha + \beta) \quad (4-8b)$$

where β is the angle between P_1 direction and P_2 direction. Then, the transmission function of the modulator $T = (E_1 + E_2) \cdot (E_1 + E_2)^*$ is deduced as

$$T = E_0^2 e^{-(\alpha_o + \alpha_e)d} [\cos^2 \alpha \cos^2(\alpha + \beta) e^{-\Delta\alpha d} + \sin^2 \alpha \sin^2(\alpha + \beta) e^{\Delta\alpha d} + 2 \sin \alpha \cos \alpha \sin(\alpha + \beta) \cos(\alpha + \beta) \cos \varphi] \quad (4-9)$$

where $\Delta\alpha = \alpha_e - \alpha_o$ describes the dichroism effect of MF. In the experiment, the analyzer P_2 is adjusted to be perpendicular to the polarizer P_1 (i.e. $\beta = 90^\circ$), hence, Eq. (4-9) is simplified as

$$T = E_0^2 e^{-(\alpha_o + \alpha_e)d} \cdot \sin^2 2\alpha \cdot [\cosh(\Delta\alpha) - \cos \varphi] / 2 \quad (4-10)$$

The transmission spectrum of the modulator is sinusoidal approximately (Figure 4-12). It is shown in Figure 4-12 that ER of the modulator is equals to ΔT . If the condition $\varphi = 2m\pi$ (m is an integer) is fulfilled, the transmission spectrum (T) is the minimum and the transmission dips appear at the corresponding wavelengths on the transmission spectrum. The wavelength space between the two adjacent transmission dips (S) is given by

$$S = \lambda^2 / (B_{PM}L - B_{MF}d) \quad (4-11)$$

A tunable laser with a narrow bandwidth is used to realize light modulation and its wavelength is selected to be coincident with the dip wavelength of the interference spectrum under zero magnetic field (e.g. 1570.2nm). It is shown in Figure 4-12 that, without the external magnetic field, the transmission power reaches its minimum. As the external magnetic field is applied, the transmission

spectrum shifts to the left and the transmission power reaches its maximum. In order to obtain the light modulation with the best ER, the spectral shift is expected to cover at least half period (S) of the spectrum.

Compared to the length of PMF (L), the thickness of MF film (d) (tens of microns) is so small that $B_{MF}d$ can be neglected, so S is mainly dependent on L . It is shown in Eq.(4-10) that the modulating ER is also affected by the fringe contrast (visibility) of the interference spectrum, which is determined by $e^{-(\alpha_o+\alpha_e)d}$ and $\sin^2 2\alpha$. In order to obtain the best visibility, α is set to be 45° . Finally, high modulating ER can be realized by selecting suitable length of PMF.

Figure 4-12 Operating principle of the magneto-optical modulator based on the magnetically controllable transmission spectrum

4.4.2 Experimental Results and Discussion

The water-based MF (EMG605, Ferrotec), whose content was 10nm-diameter ferromagnetic nanoparticles, Fe_3O_4 , was sealed between two 14mm×14mm optical glass plates to form a 15μm-thickness MF film. The concentration of the magnetic nanoparticles of the MF sample was 3.9%. The MF film was light-brown translucent. The saturated magnetization and initial magnetic susceptibility of the MF used were 220Oe and 2.96Gs/Oe, respectively. The length of the PMF (PM-1550-HP) used in the experiment was 3m and its polarization extinction ratio (PER) was higher than 40dB. The PERs of the polarizer and analyzer (Thorlabs) were both 40dB. The central wavelength of the collimators was 1550nm and the beam diameter of the collimated light was about 0.5mm. The MF film was placed amidst a uniform magnetic field which was generated with an electromagnet (LakeShore) and calibrated with a gaussmeter (LakeShore). The dimension of the uniform region was about Φ65mm×25mm and the deviation of the uniformity was better than 0.05%. The magnetic field strength can be controlled by a personal computer. The experiment was conducted at the room temperature of 23.7°C.

The transmission spectra of the magneto-optical modulator under different magnetic field strengths were measured with a broadband light source (1520-1610nm) and an optical spectrum analyzer (OSA, AQ6370), which are shown in Figure 4-12 and Figure 4-13. The fringe contrast of the transmission spectrum under zero magnetic field is about 36dB and the period is about 2.2nm. As the magnetic field strength was increased from 0Oe to 2372Oe, the transmission spectrum shifted about 1.2nm to the red side, as well as the visibility decreased from 36dB to 13dB,

gradually. In order to investigate the variation trend of the transmission spectrum, the relationship between the dip wavelength (the third dip is chosen as an example) and the magnetic field strength is shown in Figure 4-14. During the initial segment of the progression of magnetic field strength, (e.g. $H < 200$ Oe), the dip wavelength varied quickly and linearly. As the magnetic field strength increasing further, the shift of the dip wavelength became slowly and nonlinearly. As the magnetic field strength increased over a certain value (e.g. $H > 750$ Oe), the shift of the dip wavelength tended to be saturated. The curve for the decreasing process of the magnetic field strength was almost coincident with the one for the increasing process, which can be fitted well by modified Langevin function by a high goodness of fit R^2 value of 0.9982.

Figure 4-14 Dip wavelength versus the magnetic field strength

In order to verify the light intensity modulation property of the proposed modulator, a tunable laser (AQ8203) and a photodiode were applied to test the modulator. The wavelength of the tunable laser was tuned to 1570.213nm, which was coincident with the wavelength of the third dip on the transmission spectrum. The results are shown in Figure 4-15. Similar to the variation trend of transmission spectrum, the light intensity varied quickly under small magnetic field strength and tended to be saturated under large magnetic field strength. The results in the processes of increasing and decreasing of the magnetic field strength are almost coincident, which show a good reversibility and indicate that hysteric effect is absent in the MF. The curve is fitted with modified Langevin function by a R^2 value of 0.9912, which can be used to calibrate the nonlinearity between the light intensity and the magnetic field strength during the modulation.

Figure 4-15 Transmission power versus the magnetic field strength

The modulation characteristics of the proposed magneto-optical modulator are demonstrated by applying a square-wave and a sine-wave modulating magnetic fields on the MF film and the corresponding light intensity modulation results are shown in Figure 4-16. The magnetic field strengths for square-wave and sine-wave modulation were 1200Oe and 100Oe, while the corresponding ERs were about 38dB and 29dB, respectively. Limited by the speed of the magnetic field generation device, the waveform distortion appears. The frequency response of the modulator is dependent on the response time of MF, which ranged from 10ms to 600ms [155, 157, 161]. Hence, the highest frequency of such modulator is about 100Hz. The response time can further be improved by reduce concentration of the MF or by using other type of the magneto-optical material such as YIG [165, 166]. Due to the response time of MF, the modulator cannot work in high modulation frequency. However, it can be used to generate low frequency control signal in the optical communication system. Also, it is good enough for applications such as switch, routers and display.

4.4.3 Conclusion

In conclusion, the proposed magneto-optical modulator based on MF film in the polarimetric configuration is verified. The magnetically controllable birefringence property of MF plays a key role in the optical modulator. The light intensity was modulated into square-wave and sine-wave with high ERs of 38dB and 29dB, respectively. The PMF-assisted polarimetric configuration is very simple, which can be potentially developed into an integrated fiber device.

4.5 Characteristics of the Measurement Sensitivity of an Optical Fiber Sagnac Interferometric Configuration

In the experiments in Section 4.2 to Section 4.4, we found that the sensitivity or the shift range of the output transmission spectra of the proposed high-birefringence-fiber assisted optical fiber Sagnac interferometric configurations were different even when the same MF film sample was used. Therefore, we looked for the reasons in the literatures, where there were various methods for improving the sensitivity of OFSI-based sensing schemes. For instance, various types of high birefringence fibers (HBFs) including all kinds of traditional HBFs and newly emerging high birefringence photonic crystal fibers (PCFs) were incorporated into the optical fiber Sagnac interferometric configurations to compare the sensitivities [118, 120]; Special treatment processes like side polishing, chemical etching or tapering were applied to the fibers in the Sagnac loop to explore the potential [120, 167]; Functional materials such as liquid crystal, alcohol and magnetic fluid were also used to enhance the sensitivity [73, 117, 121]. The large majority of these highly birefringent OFSI-based sensors share one thing in common that is only a partial length of the birefringent fiber within the Sagnac loop acted as the sensing element. Taking the OFSI sensor based on liquid filled birefringent PCF as an example, a partial length of the PCF (20cm) was infiltrated by liquid which sensitive to the environmental temperature, whilst the remaining length of the PCF (80cm) was unfilled which also affected the sensitivity of the sensor greatly [168]. There were many more similar examples; Chen proposed OFSI sensor based on

partly chemically etched HBF for humidity measurement [167]; Sun and Dong carried out strain sensing by applying the mechanical force to a partial length of the HBF within the Sagnac loop [108, 169]; a magnetic field sensor was also implemented by inserting a magnetic film into the highly birefringent Sagnac loop [73]. We found out in this model of optical fiber Sagnac interferometric configuration, two most important parameters related to measurement sensitivity characteristics did not draw enough attention. One is the total birefringent fiber-length in the OFSI and the other is the role of the birefringence that plays in the OFSI. In the literatures, often the case, the birefringent fiber-lengths were randomly chosen or there was a tendency to choose a longer birefringent fiber-length and fiber with a higher birefringence. The improved sensitivities were all attributed to the longer birefringent fiber-length or higher birefringence used in the OFSI [73, 108, 117, 168, 170]. However, it is theoretically analyzed and experimentally demonstrated in this Section, on the contrary, a shorter length or a lower birefringence of the birefringent fiber will lead to a higher sensitivity.

4.5.1 Principle of the Sensing Configuration

A typical OFSI is configured simply by splicing a section of birefringent fiber and a single mode fiber 3dB coupler to form a Sagnac loop, which is shown in Figure 4-17. The birefringence could be intrinsic birefringence caused by anisotropic stress or structure on the transverse section of the fiber like traditional HBF, panda fiber (Inset A in Figure 4-17) or also could be induced birefringence caused by mechanical force such as transverse force, twist or bend on the fiber [98, 119].

Figure 4-17 Schematic diagram of the structure of the OFSI; Inset A: the cross section of traditional PMF pander fiber; Inset B: the cross section of LBF, solid core PCF (LMA-10)

In Figure 4-17, the whole length of the birefringent fiber within the Sagnac loop contributes to its output spectrum which is denoted as L , whilst a partial length of the birefringent fiber functions as birefringence sensitive element for sensing measurement, which is denoted as L_0 . Subsequently, a phase difference is introduced between the orthogonal guiding modes as the light beams counterpropagate along the Sagnac loop due to the birefringence effect of the birefringent fiber. Hence, a sinusoidal interference spectrum is observed as the two beams beat together again at the coupler, which is given in Section 3.3

$$T = (1 - \cos \varphi) / 2 \quad (4-12)$$

where $\varphi = 2\pi BL / \lambda$ is the total phase difference between the two orthogonal linearly polarized modes; BL is the corresponding optical path difference (OPD), where B and L are the birefringence and length of the birefringent fiber, respectively; λ is the operating wavelength of the light; If the condition $\varphi = 2\pi m$ (m is an integer) is fulfilled, the transmission spectrum reaches its minimum, where m is the fringe order of the transmission dip. Subsequently, the wavelength of the m -th order

fringe on the transmission spectrum can be given as

$$\lambda_m = BL/m \quad (4-13)$$

Hence, the period of the interference spectrum or the spectral space between the adjacent two transmission dips (S) can be given by

$$S = \lambda^2 / BL \quad (4-14)$$

Eq.(4-14) shows that the period (S) is inversely proportional to the OPD (BL).

Usually, the measurement sensitivity of the OFSI sensors is described by the spectral shift or dip wavelength shift. From Eq.(4-13), the sensitivity can be deduced as

$$\Delta\lambda = \Delta BL_0 / m \quad (4-15)$$

Eq.(4-15) shows that the sensitivity is inversely proportional to the interference fringe order (m). Higher sensitivity can be achieved at lower order (m), which is corresponding to the dips at the shorter wavelength side.

Eq.(4-15) is the most often used expression of the sensitivity in the literatures, but the two key parameters B and L do not appear in this equation [117].

Hence another expression of the sensitivity can be deduced by [108]

$$\Delta\lambda = \frac{\Delta\varphi}{2\pi} S = \frac{\Delta BL_0}{BL} \lambda \quad (4-16)$$

Eq.(4-16) shows that the measurement sensitivity is inversely proportional to the OPD (BL). In other words, higher sensitivity can be achieved by reducing OPD, i.e. reducing the length L or the birefringence B or both. However, as concluded by Eq.(4-14), if BL is too small, the period S will be so large that it will exceed the spectral range of the measurement devices. Hence, BL should be optimized in a suitable range.

4.5.2 Experimental results and Discussion

In order to verify the above predictions, three OFSIs with different lengths of HBF were fabricated. The characteristics of the three OFSIs were verified by taking a strain test. The HBF employed in the Sagnac loop was a traditional polarization maintaining fiber (PMF), panda fiber (PM-1550-HP), whose cross section is shown in the inset A in Figure 4-17. The birefringence of the HBF was 3.3×10^{-4} . The corresponding HBF-lengths in the three OFSIs were 6.5cm, 17.1cm and 52.2cm, respectively, which were assigned as OFSI A, B and C for convenient description. A section of HBF was removed from coating and attached to the translation stages with a resolution of 0.01mm for strain applying. The fixed lengths of HBF for the OFSI A, B and C were the same, which were 5cm. The central wavelength of the single mode fiber 3dB coupler used in the Sagnac loop was 1550nm. The transmission spectra were monitored with an amplified spontaneous emission (ASE, 1520-1620nm) light source and an optical spectrum analyzer (OSA, AQ6370).

The transmission spectra of the OFSI A, B and C are showed in Figure 4-18. They are all similar sinusoidal waveforms, whose fringe contrasts (peak-to-peak ratios) are about 30dB. The differences among the three spectra are their periods, which are 58.52nm, 19.58nm and 8.89nm for OFSI A, B and C, respectively. This result shows that the period of the spectrum is inversely proportional to the HBF-length, which well supports the prediction of Eq.(4-14). As the HBF-length in the OFSI is decreasing, the total numbers of the transmission dips appear on the spectra are also decreasing. It indicates that the HBF with adequate length, i.e. the adequate OPD, is necessary in the OFSI for sensing applications, otherwise no transmission

dip will appear and sensing measurement cannot be performed.

Figure 4-18 Transmission spectra of the OFSI sensors with different HBF-lengths (a) 6.5cm (b) 17.1cm (c) 52.2cm

In order to compare the sensitivity characteristics of the three OFSIs, the same amount of strain was applied on the HBFs from 0mε to 4mε with an interval of 0.4mε through the translation stages. The leftmost dip on the transmission spectrum of OFSI A was chosen as an example to show detailedly the variation trend in Figure 4-19. A red shift from 1526.16 to 1605.46nm, totally 79.30 nm, occurred as the strain was increased from 0mε to 4mε.

The relationships between the strain and the dip wavelengths of the transmission spectra for the 3 OFSIs are shown in Figure 4-20. The linear fit method was applied to the curves by a high goodness of fit R^2 values. The corresponding sensitivities of OFSI A, B and C are 19.58pm/με, 6.408pm/με and 2.438pm/με, respectively. The sensitivity of OFSI A is about 8 times better than the OFSI C. This result well supports the prediction of Eq.(4-16), i.e. smaller OPD introduced by shorter length of HBF L will lead to a higher sensitivity.

Figure 4-20 Relationship between the dip wavelength and the applied strain

The influence of fringe order (m) was also verified in the experiment. The transmission spectrum of OFSI B was taken as an example, which is shown in Figure 4-21(b). Five transmission dips appear on the transmission spectrum when no strain is applied on the HBF. The rightmost transmission dip occupies the lowest fringe order, which is indicated (m) in Figure 4-21(b). The transmission spectrum shifted to the red side as the increase of the applied strain. Subsequently, the transmission dip of m -th order shifted to the right out of the spectrum range of the light source and the one of order $m+4$ shifted from the left into the spectrum range.

The relationship between the strain and dip wavelengths of all the orders are plotted in Figure 4-21. The sensitivities are also calculated by the linear fit method which are 7.0579pm/ $\mu\epsilon$, 6.6123pm/ $\mu\epsilon$, 6.5162pm/ $\mu\epsilon$, 6.4518pm/ $\mu\epsilon$ and 6.4069pm/ $\mu\epsilon$, respectively, corresponding to from the lowest to the highest order. It shows that the transmission dip of lower order, i.e the dip at the longer wavelength side, exhibits higher sensitivity, which is predicted by the Eq.(4-14). Comparing the results of the three OFSIs, it is also worth noticing that, as the length of HBF

increasing, the sensitivity difference among transmission dips of different orders become smaller.

Figure 4-21 Sensitivities of the transmission dips of different orders for the sensor with different HBF-lengths (a) 6.5cm (b) 17.1cm (c) 52.2cm

Since the OPD depends both on birefringence B and length of birefringent fiber (L) whilst the sensitivity depends on the OPD predicted by Eq.(4-16), hence the sensitivity of the OFSI also depends on the birefringence of the birefringent fiber (B). A low-birefringence fiber (LBF) was employed in the Sagnac loop and a temperature sensing experiment was performed to prove the prediction by Eq.(4-16). The LBF used was a solid core photonic crystal fiber (PCF), which is shown in inset B in Figure 4-17. The LBF has a circularly symmetric hexagonal structure, whose birefringence value was calculated to be in a order of magnitude 10^{-6} according to the results in the reference [171]. As discussed previously, necessary birefringence is needed in the OFSI for sensing measurement, so a transverse force is applied on the LBF to introduce an initial birefringence as small as possible into the Sagnac loop with the same method as the ones in Section 3.3 and Section 3.4.

The output transmission spectrum of this optical fiber Sagnac interferometric configuration is a sinusoidal waveform, which is shown in Figure 4-22. Only one transmission dip appears in the spectral range from 1520nm to

1620nm, thus the introduced birefringence value can be calculated to be smaller than 4.8×10^{-5} , which indicates this OFSI is low birefringent Sagnac loop.

The partial length of the LBF, where the initial transverse force was applied on, was heated to test the sensitivity performance. As shown in Figure 4-22, the transmission dip was shifted from 1534.5nm to 1581.4nm totally 46.9nm as the temperature was increased from 18.5°C to 20.0°C.

Figure 4-22 Transmission spectrum of the sensor shifts with

The relationship between the temperature and the dip wavelength is plotted in Figure 4-23. The linear fit method is applied to the data by a high goodness of fit R^2 value of 0.9941. The temperature sensitivity of this proposed low birefringence OFSI is calculated to be 30.33nm/°C. This sensitivity result is even 5 times better than the best reported results in the literatures [117, 168]. Therefore, the sensitivity of the OFSI can be improved by decreasing the birefringence (B) of the birefringent fiber within the Sagnac loop. The experimental result well supported the theoretical

prediction of Eq.(4-16).

Figure 4-23 Relationship between the dip wavelength and the temperature

4.5.3 Conclusion

In conclusion, the sensitivity characteristics of the optical fiber Sagnac interferometric configuration are theoretically analyzed and experimentally verified through a strain sensing experiment and a temperature sensing experiment. The measurement sensitivity of the optical fiber Sagnac interferometric configuration can be improved by using shorter length of HBF, monitoring the transmission dip of lower fringe order or decreasing the birefringence within the Sagnac loop. In the next Section, we will apply the conclusions drawn from this Section to the magnetic field sensor proposed in Section 4.2 to improve the sensitivity.

4.6 Enhancement of the Sensitivity of a Magnetic Field Sensor Based on Optical Fiber Sagnac Interferometric Configuration

Section 4.5 not only answers the question why the results of the sensitivity or the total wavelength shift range are quite different from Section 4.2 to Section 4.4, but also gives some guidance on how to improve the sensitivity of OFSI-based sensors. In this Section, we will apply the conclusions drawn from Section 4.5 to the OFSI-based magnetic field sensor, which is proposed in Section 4.2. The corresponding measurement sensitivity is expected to be improved dramatically.

4.6.1 Principle of the Sensing Configuration

A highly birefringent Sagnac loop containing two Sections of high birefringence fiber (HBF) is referred to as Loyt-Sagnac interferometer or two order Sagnac interferometer, whose typical configuration is shown in Figure 4-24. Light launched from the input port of the coupler is split into two beams that counterpropagate along the Sagnac loop. The two beams accumulate phase differences when they pass through the two sections of HBFs and interfere when they beat together at the coupler. Assuming a 3dB coupler is used, the relative transmittance of the Loyt-Sagnac interferometer can be obtained with the Jones Matrix method [130],

$$T = \left[\cos\left(\frac{\varphi_1 + \varphi_2}{2}\right) \sin(\theta_1 + \theta_3) \cos \theta_2 + \cos\left(\frac{\varphi_1 - \varphi_2}{2}\right) \cos(\theta_1 + \theta_3) \sin \theta_2 \right]^2 \quad (4-17)$$

where φ_1 and φ_2 are the phase differences between the two orthogonal modes

caused by HBF₁ and HBF₂ respectively. θ_1 and θ_3 are the angles between the polarization directions of counterpropagating beams and the corresponding fast axes of the two section of HBFs. θ_2 is the angle between the fast axes of the two sections of HBFs. Usually, $\theta_1 + \theta_3$ can be controlled by a polarization controller in order to obtain a high fringe contrast, but the polarization controller is not an essential component.

Figure 4-24 Schematic diagram of a typical Loyt-Sagnac interferometer

In the proposed magnetic field sensor based on the Loyt-Sagnac interferometric configuration, a section of PMF is in the position of HBF₁ while a MF film is in the position of HBF₂ with the assistance of a pair of fiber collimators. The setup is the same as Figure 4-1. Besides the birefringence effect of MF film, the dichroism effect is also considered. The fast axes are aligned between the PMF and the MF film ($\theta_2 = 0$) in order to obtain the best sensitivity. The relative transmittance of this optical fiber Loyt-Sagnac interferometric configuration is re-

deduced as

$$T = 2 \exp[-(\alpha_o + \alpha_e)d] \cdot \sin^2(\theta_1 + \theta_3) \cdot [\cosh(\alpha_o - \alpha_e)d + \cos(\varphi_{PMF} + \varphi_{MF})] \quad (4-18)$$

where $\varphi_{PMF} = 2\pi B_p L / \lambda$ is the phase difference introduced by the birefringence effect (B_p) of PMF over the length L ; $\varphi_{MF} = 2\pi B_m L / \lambda$ is the phase difference accumulated by the birefringence effect (B_m) of MF film over the thickness (d). α_e and α_o related to the dichroism effect of MF are the absorption coefficients for the two orthogonal modes. The transmission spectrum is an approximately cosinusoidal waveform whose fringe contrast depends on the dichroism effect item $\exp[-(\alpha_o + \alpha_e)d]$ and whose period depends on the periodic function item $\cos(\varphi_{PMF} + \varphi_{MF})$. The dip wavelengths of the transmission spectrum can be obtained when the condition $\varphi = \varphi_{PMF} + \varphi_{MF} = (2m+1)\pi$ (m is an integer) is fulfilled. Hence, the period of the transmission spectrum can be obtained by calculating the wavelength spacing between the adjacent dips,

$$S = \lambda^2 / (B_p L + B_m d) \quad (4-19)$$

The transmission dips of the spectrum shift with the variation of the external magnetic field. Therefore, the magnetic field strength can be measured by monitoring the dip wavelength of the transmission spectrum. The sensitivity of the sensor ($\Delta\lambda$), which is defined by the shift of the dip wavelength, can be estimated by [108]

$$\Delta\lambda = \frac{\Delta\varphi}{2\pi} S = \frac{\Delta B_m d}{B_p L + B_m d} \lambda \quad (4-20)$$

Subjected to the huge transmission loss of the MF film itself, the thickness of MF

film is usually limited to thinner than $100\mu\text{m}$. Therefore, we have $B_p L \gg B_m d$.

Subsequently, Eq.(4-20) is simplified as,

$$\Delta\lambda \approx \frac{\Delta B_m d}{B_p L} \lambda \quad (4-21)$$

Eq.(4-21) shows that the sensitivity of the sensor is inversely proportional to the length of PMF (L) but proportional to the thickness of MF film (d). In order to enhance the sensitivity, we need to reduce L , but, in practice, the PMF cannot be shortened without any limitation, because $B_m d$ is so small that S generated solely by MF film itself according to Eq.(4-19) will be too large and exceed the optical spectral range of the light source.

Briefly, the purpose for introducing PMF into the Sagnac loop is to assist the sensor in generating cosinusoidal transmission spectrum with suitable period and making the spectrum ‘visible’ on the measurement devices in the optical communication wavelength range. The sensitivity of the sensor can be enhanced by shortening the length of PMF or increasing the thickness of MF film.

4.6.2 Experimental Results and Discussion

The optical components used in this experiment were completely the same as the experiment in Section 4.2. The PMF used in the experiment was a traditional pandar fiber (PM-1550-HP), whose birefringence was 3.3×10^{-4} . The water-based MF sample (EMG605 Ferrotech) used in the experiment was prepared with the coprecipitation technique, whose birefringence was estimated to be $\sim 10^{-3}$ [63]. The containment of the MF samples was Fe_3O_4 nanoparticles with nominal diameter of 10nm and the volume concentration of nanoparticles was 3.9%. The MF films were

prepared simply by sealing the MF drops between two $22 \times 22 \text{ mm}^2$ glass slides with glue. The thicknesses of the MF film samples were in a range of several tens of microns. In the configuration, the applied magnetic field generated by an electromagnet (EM4-HVA, Lakeshore) was set parallel to the plane of MF film while the light path was perpendicular to the plane to the plane of MF film. The magnetic field strength was monitored by a Gaussmeter with a transverse probe (Model 425, Lakeshore). An amplified spontaneous emission light source (ASE, 1520nm-1620nm) and an optical spectrum analyzer were employed to record the transmission spectra of the sensors. The experiment was carried out in the room temperature of 24.3°C .

First, in order to verify the predictions by Eq.(4-21), three Loyt-Sagnac interferometers were prepared by employing PMF with different lengths. The PMF-lengths employed in the three Loyt-Sagnac interferometers were 300cm, 50cm and 2cm, which are assigned as sensor A, B and C, respectively, for convenient description. The MF film sample with a thickness of $40\mu\text{m}$ was employed in the three Loyt-Sagnac interferometers. The sensitivities of the three sensors were compared during the magnetic field sensing test.

The transmission spectra of the three sensors under zero magnetic field are shown in Figure 4-25. They are all similar cosinusoidal waveforms with high fringe contrasts ($>30\text{dB}$). According to Eq.(4-19), the periods of the transmission spectra are inversely proportional to the PMF-length, which are 2.16nm, 11.25nm and $>100\text{nm}$ for the sensor A, B and C respectively.

Figure 4-25 Transmission spectra of the proposed sensors with different lengths of PMF (a) 300cm (b) 50cm (c) 2cm

The variation trends of the transmission spectra for the three sensors under external magnetic field are similar. Taking the third transmission dip of sensor B as an example (Figure 4-26), the transmission spectrum shifts to the longer wavelength side from 1565.45nm to 1568.58nm totally 3.13nm and the fringe contrast declines gradually from 32dB to 15dB as the applied magnetic field strength is increased from 0Oe to 2013Oe. The decline of the fringe contrast was caused by the dichroism effect of MF, which is predicted in Eq.(4-18).

The relationships between the dip wavelengths of the transmission spectra of the three sensors and the magnetic field strength are shown in Figure 4-27. When the magnetic field strength is smaller than a certain strength (e.g. $H < 200\text{Oe}$), the wavelength shift increases rapidly and linearly with the external magnetic field strength. When the magnetic field strength passes a certain strength (e.g. $H > 500\text{Oe}$), the wavelength shift saturates gradually. Comparing the results of the three sensors, the variation trends, which follow a Langevin function, are similar, but the total wavelength shifts are different, which are 0.67nm, 3.13nm and 46.68nm for sensor A, B and C respectively. Linear fit method is applied to the linear regions of the

three curves and the sensitivities of 2pm/Oe, 14.9pm/Oe and 218.4pm/Oe are obtained for sensor A, B and C respectively. The results well support the predictions by Eq.(4-21). Therefore, the birefringence is magnified by using short length PMF in this Løyt-Sagnac interferometric configuration.

Figure 4-26 Transmission spectra of sensor B under different applied magnetic field strengths

Figure 4-27 Dip wavelengths of the transmission spectra v the magnetic field strength for the sensors with different PMF-lengths (a) 300cm (b) 50cm (c) 2cm

In order to further compare and improve the sensitivity performance, the MF film sample with thickness of $40\mu\text{m}$ in sensor C was replaced by another two MF film samples with corresponding thicknesses of $20\mu\text{m}$ and $70\mu\text{m}$. The results are shown in Figure 4-28. The achieved sensitivities are 126.7pm/Oe , 218.4pm/Oe and 592.8pm/Oe for the MF film samples with thickness of $20\mu\text{m}$, $40\mu\text{m}$ and $70\mu\text{m}$. As for the reported MF-based magnetic field sensors, the sensitivity results of the sensors based on FBG, FPI, MZI and PCF were 0.344pm/Oe [153], 1.25pm/Oe [115], 2.37pm/Oe [172] and 24.2pm/Oe [173] respectively. Compared with the above results, our achieved sensitivity result (592.8pm/Oe) is well enhanced.

Figure 4-28 Dip wavelengths of the transmission spectra vs the magnetic field strength for the sensors with different MF-thickness (a) $20\mu\text{m}$ (b) $40\mu\text{m}$ (c) $70\mu\text{m}$

4.6.3 Conclusion

In conclusion, a magnetic field sensor based on Loyt-Sagnac interferometric configuration is discussed. By applying the conclusions drawn from Section 4.5 to

this sensing configuration, the sensitivity of the sensor is enhanced. The sensor takes advantage of the birefringence effect of MF film. In the configuration, the PMF is employed to provide constant bias phase difference which makes the transmission spectrum visible on the measurement devices whilst the MF film provides variable phase difference for measurement. The achieved best sensitivity is 592.8pm/Oe, which is 1-3 orders of magnitude better than the reported results of the other MF-based sensors. The sensitivity of this proposed sensor also has much room to be improved by further reducing the PMF-length.

Besides, the experimental results can be used as guidelines for designing the magneto-optical modulators in Section 4.3 and Section 4.4.

4.7 Laser Self-Induced Tunable Birefringence of Magnetic Fluid

Sections 4.2-4.6 have discussed detailedly how to apply the linear birefringence effect of MF to realize magnetic field sensors and magneto-optical modulators and how to enhance the measurement sensitivity. In the experiment in this Section, the laser self-induced tunable birefringence phenomenon of the MF film is observed by taking advantage of the high-birefringence-fiber assisted polarimetric configuration. This phenomenon can be observed both in the zero field birefringence effect and magnetic field induced birefringence effect in the MF film. Besides, the dichroism effect does not occur in the zero field birefringence effect but appears in the field induced birefringence effect, which has also been observed in this experiment.

4.7.1 Principle of the Laser Self-Induced Tunable Birefringence

The setup was completely the same as the one in Section 4.4. The schematic diagram of the experimental setup for observing the laser self-induced tunable birefringence effect is shown in Figure 4-29. This optical-fiber based setup was similar to the traditional setup for measuring the birefringence effect of MF [63], but an extra high birefringence fiber was inserted between the polarizer and the analyzer to introduce more phase difference. Light from a broadband light source became collimated light through a single mode fiber (SMF) collimator, then became linearly polarized light through the polarizer, accumulated phase difference in turn through the high birefringence fiber as well as the MF film, produced interference fringes at the analyzer, and finally went through the collimator to an OSA for monitoring the interference spectrum.

The anisotropic MF film can be treated as a typical birefringent material like uniaxial crystal or high birefringence fiber with its slow axis parallel to the magnetic field direction and fast axis perpendicular to the magnetic field direction [75]. As shown in Figure 4-29, the magnetic field direction was parallel to the MF film and perpendicular to the light propagation direction. Meanwhile the fast axis of the MF film was aligned parallelly with the slow axis of the high birefringence fiber. The polarizer and the analyzer were also adjusted so that the angle between their polarization directions was 90°. Hence, the relative transmittance of the polarimeter can be given by [172]

$$T = e^{-(\alpha_o + \alpha_e)d} \cdot \sin^2(2\theta) \cdot [\cosh(\alpha_o - \alpha_e)d - \cos\varphi] \quad (4-22)$$

where θ is the angle between the polarization direction of the polarizer and the fast axis of the high birefringence fiber. α_o and α_e are the absorption coefficients of the MF film which are related to the dichroism effect of MF. α_o is the absorption coefficient corresponding to the light polarization component parallel to the fast axis of MF film (ordinary ray) whilst α_e is the one parallel to the slow axis (extraordinary ray).

$\varphi = \varphi_{HBF} - \varphi_{MF}$ is the total phase difference, where $\varphi_{HBF} = 2\pi B_{HBF} L / \lambda$ is a constant phase difference which is induced by the high birefringence fiber whilst the $\varphi_{MF} = 2\pi B_{MF} d / \lambda$ is a variable phase difference which is induced by the MF film. B_{HBF} and L are the birefringence and length of high birefringence fiber, respectively; B_{MF} and d are the birefringence and thickness of MF film, respectively. λ is the operating wavelength of the light.

Figure 4-29 Schematic diagram of high-birefringence-fiber assisted polarimeter

The transmission spectrum of this polarimetric configuration is an approximately periodical cosinusoidal waveform, which is shown in Figure 4-30. The peak-to-peak ratio (fringe contrast, or visibility) of this transmission spectrum is affected by the item $e^{-(\alpha_o + \alpha_e)d}$. In the absence of the dichroism effect, $\alpha_o \approx \alpha_e$, both of which remain constant during the process of the variation of the external magnetic field strength, therefore the peak-to-peak ratio remains the same. In the presence of dichroism effect, $\alpha_o \neq \alpha_e$, which increase with the external magnetic field strength, therefore the peak-to-peak ratio will decrease accordingly. This phenomenon can be used to estimate whether the absorption coefficients (α_o & α_e) of the MF film change distinctly or not.

The period of the transmission spectrum is dependent on the total phase difference (φ). If the condition $\varphi = 2m\pi$ (m is an integer) is fulfilled, the dip wavelength can be obtained as

$$\lambda_m = (B_{HBF}L - B_{MF}d)/m \quad (4-23)$$

Hence, the variation of the dip wavelength with the external magnetic field strength can be given by

$$\Delta\lambda_m = -\Delta B_{MF}d/m \quad (4-24)$$

Eq.(4-24) shows that the variation of the birefringence of MF film under external magnetic field can be observed by monitoring the dip wavelengths of the transmission spectrum. If the birefringence of MF film increases, the transmission dip will shift to the shorter wavelength side accordingly.

Figure 4-30 Transmission spectrum of high-birefringence-fiber assisted polarimeter

4.7.2 Experimental Results and Discussion

In the experiment, the high birefringence fiber used was a 70-cm-length polarization maintaining fiber (PMF), whose birefringence was about 3.3×10^{-4}

(PM-1550-HP). The MF used was a water-based MF (EMG605, Ferrotec), which contained the ferromagnetic nanoparticles, Fe_3O_4 , and their nominal diameters were 10nm. The concentration of the MF was 3.9%; the saturated magnetization was 220Oe; the initial magnetic susceptibility was 2.96Gs/Oe.

The MF film sample was prepared simply by sealing the MF between two $22 \times 22 \text{ mm}^2$ glass slides and its net thickness was about $30 \mu\text{m}$. An electromagnet (EM4-HVA, Lakeshore) was employed to generate uniform static magnetic field with an accuracy of 0.01Oe, whose strength was calibrated by a gaussmeter (Model 425, Lakeshore). The MF film was placed completely amidst the uniform field zone. The broadband light source used was an amplified spontaneous emission (ASE) source, whose spectral range was 1520nm-1620nm and whose maximum power is about 200mW. The laser power was measured with an optical powermeter. The spectrum was monitored by an OSA (AQ6370). The central wavelength of the collimators was 1550nm. The polarization extinction ratios of the polarizer and the analyzer (Thorlab) were better than 40dB. The experiment was carried out at the room temperature of 24.5°C .

In order to observe the laser self-induced tunable birefringence effect, a series of transmission spectra of the polarimeter were recorded under zero magnetic field as the laser power was increased from 0mW to 20mW with an interval of about 2mW. The laser power here was the power which actually reached the MF film. The initial overall transmission spectrum under zero magnetic field is shown in Figure 4-30, which has a high peak-to-peak ratio of about 33dB.

The rightmost dip on the transmission spectrum was chosen as an example for monitoring the spectral shift (Figure 4-31). It can be seen in Figure 4-31 that the

transmission dip shifts to the shorter wavelength side from 1572.56nm to 1571.22nm totally 1.34nm as the laser power is increased from 0mW to 20mW. The peak-to-peak ratio of the transmission spectrum remains almost unchanged, but the overall power level of the transmission spectrum increases due to the increase of the laser power.

Figure 4-31 Transmission spectrum shifts with laser power under zero magnetic field

During the process, every time when the laser power was suddenly increased by about 2mW, the transmission spectrum responded immediately but shifted slowly and gradually with a declining speed. It took about 10-15mins for the spectral shift to stabilize. We consider the laser self-induced thermal effect is responsible for the change of birefringence, which heats the MF film and meanwhile creates a temperature gradient field in the MF film as well as causes the nanoparticle concentration to be redistributed [74]. This phenomenon is also referred to as the thermal lens effect of MF in the literatures [24, 74]. Subsequently,

the nanoparticles in the MF film gain more kinetic energy and promote the spontaneous formation of the orientated dimmers, so the birefringence of MF film is increased.

The relationship between the dip wavelength shift of the transmission spectrum and the incident laser power is plotted in Figure 4-32. The variation trend follows a linear function. The linear fit method is applied to the data and the slope is 0.0644nm/mW.

Figure 4-32 Shift of the dip wavelength of the transmission spectrum with laser power under zero magnetic field

In order to compare the birefringence effect tuned by laser power with the one tuned by external magnetic field, a series of transmission spectra were recorded in Figure 4-33 as the magnetic field strength was increased. The laser power was 20mW in this experiment. The transmission dip on the spectrum was also shifted to the shorter wavelength side from 1574.80nm to 1573.69nm totally 1.11nm whilst the peak-to-peak ratio of the transmission spectrum was decreased gradually from

about 33dB to 12dB totally 21dB during the process of the magnetic field strength was increased from 0Oe to 1360Oe.

Figure 4-33 Transmission spectrum shifts with external magnetic field

Compared to the result in Figure 4-33, the significant difference is the decrease of the peak-to-peak ratio of the transmission spectrum which is related to dichroism effect of MF. This is because in the presence of external magnetic field, the nanoparticles form magnetic chains significantly and align along the magnetic field direction [151, 174]. The formation of the magnetic chains exhibits significant different absorption coefficients for the two beams for interference, i.e. the ordinary ray and extraordinary ray, which leads to the significant decline of the peak-to-peak ratio of the interference spectrum. However, in the case of the absence of the external magnetic field, the zero field birefringence is originated from the spontaneous formation of orientated dimers, so there is no such strong formation of magnetic chains which cause strong dichroism effect [68].

The relationship between the dip wavelength of the transmission spectrum and the external magnetic field strength is shown in Figure 4-34. During the process of the increase of the magnetic field strength, when the magnetic field strength was smaller than the 'critical field strength' ($H_c=32.8\text{Oe}$), the transmission spectrum remained unchanged [12]; and then the transmission spectrum shifted quickly and linearly with the increase of the magnetic field strength (e.g. $32.8\text{Oe}<H<300\text{Oe}$); and then the transmission spectrum shifted slowly and tended to saturate gradually. The curve follows a Langevin function, which is different from the linear result in Figure 4-34.

Figure 4-34 Shift of the dip wavelength of the transmission spectrum with external magnetic field

The phenomenon of laser self-induced tunable birefringence effect of MF under external applied magnetic field was also observed for comparison. The external magnetic field strength was 2325Oe , which was a deep saturation strength for this MF film according to the result in Figure 4-33. Since the peak-to-peak ratio

of the transmission spectrum declined greatly in the presence of such a strong magnetic field, the analyzer in the setup was rotated to balance the intensities of the two beams for interference so that the peak-to-peak ratio could return to its maximum value. A series of transmission spectra were recorded under external magnetic field as the laser power was increased (Figure 4-35). It is shown in Figure 4-35 that the transmission dip shifts to the shorter wavelength side from 1571.44nm to 1570.54nm totally 0.9nm as the laser power was increased from 0mW to 20mW. The phenomenon is similar to the one in Figure 4-31, but the total wavelength shift range (0.9nm) is smaller than the one in Figure 4-31 (1.34nm).

Similarly, the relationship between the dip wavelength shift of the transmission spectrum and the laser power is a linear function (Figure 4-36). Linear fit is applied to the data and the corresponding slope is estimated to be 0.0413nm/mW, which is also smaller than the result in Figure 4-32 (0.0644nm/nW).

The reason why the laser self-induced tunable birefringence is suppressed is due to the presence of the external magnetic field. The nanoparticles gained more magnetic energy under external magnetic field, therefore more kinetic energy from laser power is needed to reestablish the state of balance [24].

Figure 4-36 Shift of the dip wavelength of the transmission spectrum with laser power under a 2325 Oe strength magnetic field

4.7.3 Conclusion

In conclusion, phenomena of laser self-induced tunable birefringence effects of MF have been observed by using the polarimetric configuration, which means the birefringence of MF, can be changed by the laser power itself. This phenomenon exists in MF film no matter whether the external magnetic field is applied or not, but the laser self-induced tunable birefringence effect will be suppressed in the presence of external magnetic field in terms of the tunable range and slope. The variation trend of the birefringence effect of MF film with laser power follows a linear relationship. The birefringence effect of MF under different external magnetic field strengths is also tested by taking advantage of the same

setup for comparison, whose variation trend is a Langevin function. Another distinct difference is the dichroism effect, which does not coexist with the laser self-induced tunable birefringence effect but is always coupled with the magnetic field induced birefringence effect.

The birefringence effect of MF changes with the laser power, so the applications based on the birefringence effect of MF, which are presented in Section 4.2 to Section 4.6, require the laser power should be kept stable, or else these MF-based devices cannot work properly. Besides, the phenomena of laser self-induced tunable birefringence effect are the thermal effect of the MF in nature. Therefore, the environment temperature of these MF-based devices should be kept stable.

4.8 Chapter Summary

In this Chapter, we have modified the optical fiber Sagnac interferometric configuration used in the Chapter 3 in order to apply the birefringence effect of MF in the OFSI to realize the MF-based optical fiber devices including magnetic field sensors and magneto-optical modulators. Besides, we have observed laser self-induced tunable birefringence effect in the experiment.

The modified optical fiber Sagnac interferometric configuration is in essence a Loyt-Sagnac interferometer. It is called HBF-assisted OFSI in this particular occasion because the extra high birefringence fiber used in the configuration solely provides constant phase difference for bias purpose whilst the MF film provides variable phase difference for measurement. Without the high birefringence fiber, the transmission spectrum of the OFSI cannot be ‘visible’ on

the measurement devices due to the small phase difference introduced by the MF film. Hence this HBF-assisted optical fiber Sagnac interferometric configuration can magnify the relative small phase difference.

Taking full advantage of this HBF-assisted optical fiber Sagnac interferometric configuration, a magnetic field sensor by inserting MF film in the Sagnac loop is demonstrated with an attempt to improve the sensitivity. The achieved sensitivity of the proposed sensor is about 1-2 orders of magnitude better than the results in the literatures. Through further investigations, we find that the sensitivity of the HBF-assisted OFSI can be further improved by using shorter length of HBF in the Sagnac loop. A temperature sensor is carried out for verifying this prediction and its temperature is even 5 times better than the best result in the literatures. The sensitivity of the proposed magnetic field sensor is also improved by using shorter length of HBF. The achieved best sensitivity is further improved by 1 order of magnitude.

Taking full advantage of this HBF-assisted optical fiber Sagnac interferometric configuration, we also demonstrated a magneto-optical fiber modulator with an attempt to improve the extinction ratio. The extinction ratios of the most MF-based modulators reported in the literatures were around 1dB. The achieved extinction ratio in this modulator is about 19.5dB. After that, we find if some requirements are fulfilled, the extinction ratio can be further improved. Therefore, we have proposed a similar magneto-optical modulator based on the polarimetric configuration and the extinction ratio is further improved to 38dB.

Taking advantage of this HBF-assisted polarimetric configuration, a laser self-induced tunable birefringence of MF has also been observed. This phenomenon

appears in both the zero field birefringence effect and the field induced birefringence effect of MF, but this phenomenon will be suppressed in the presence of external magnetic field. Meanwhile, no dichroism effect of MF is observed in the laser self-induced tunable birefringence effect, which is always coupled with the field induced birefringence effect.

In next Chapter, we will use the tunable refractive index property of MF for the development of fiber optics applications.

Chapter 5 Development of the Fiber Optics Applications by Using Tunable Refractive Index Property of Magnetic Fluid

5.1 Introduction

In Chapter 4, we have discussed the fiber optics applications by using the birefringence property of MF including magnetic field sensors and magneto-optical modulators. In this Chapter we will continue exploring the possibility of developing the fiber optics applications by using the tunable refractive index property of MF. Especially, we will focus on the newly emerged fiber family, photonic crystal fibers (PCFs).

As reviewed in Chapter 2, one of the significant differences of PCFs from traditional optical fibers is their flexible air-hole structures. By means of flexibly designing their air-hole structures, some special properties of PCFs can be enhanced for optical communication applications. However, in the area of optical fiber sensors, two unique properties of PCFs attract more research interest and are most commonly used, namely the evanescent field property of the PCFs with air-holes collapse and fillable air-hole structure of PCFs. By combining the tunable refractive index property and the fluidity of MF, there can be many potential applications. In this Chapter, we will explore these possibilities. Firstly, an optical fiber magnetic field sensor based on the evanescent field property of a PCF with air-holes collapse

is developed and then another kind of optical fiber magnetic field sensor based on the photonic bandgap effect of liquid-filled PCF is discussed.

5.2 Development of a Magnetic Field Sensor Based on Photonic Crystal Fiber with air-holes collapse¹⁰

Usually, the air-hole structure of PCFs will be collapsed during the process of fusion splice because of the heat generated by electric arc. This collapse of air-holes will introduce extra insertion loss, which is a disadvantage to optical fiber communication applications. However, this collapse of air-holes can be used in the optical fiber sensors [109, 175-181]. Because the structure of the PCF with air-holes collapse is destroyed, hence light propagating in the PCF cannot be fully confined in the core area of the PCF and will expand out of the fiber. This expanded light field is named as evanescent field, which can interact with ambient dielectric environment for sensing measurement. Besides, the guiding mode property of a PCF with collapsed air-holes is modified from single mode state to multimode state, which can be used for producing modal interference. By taking advantage of this modal interference of PCF with air-holes collapse, Mach-Zehnder interferometer can be formed for various parameter measurements such as strain, micro-bending, temperature, ambient dielectric environment and so on [180-183]. In this Section, a magnetic field sensor is presented by combining the tunable refractive index property of the MF and the Mach-Zehnder interferometer based on the PCF with air-holes collapse.

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5.2.1 Principle of the Sensing Configuration

The configuration of the proposed magnetic field fiber sensor is illustrated in Figure 5-1, which is based on a Mach-Zehnder interferometer with the MF serving as its outer cladding layer. The Mach-Zehnder interferometer is a “sandwich” structure which was fabricated simply by splicing a section of 20-mm-length photonic crystal fiber (LMA-10) between two sections of single mode fibers.

The photonic crystal fiber was prepared with a mechanical cleaver and spliced with a common commercial available fusion splicer (Fujikura FSM-40S). The default parameters for splicing single mode fibers were used, but the arc position was slightly moved to the photonic crystal fiber side (about 50 μ m) in order to collapse the air-hole cladding of the photonic crystal fiber effectively. Subsequently, the photonic crystal fiber near the splicing point was converted into a

solid silica “rod”. The overall length of the collapsed region was approximately 300 μ m which is shown in Figure 5-1(b). The SMF-PCF-SMF sandwich structure, which actually formed an optical Mach-Zehnder interferometer, was inserted into a 30-mm-length glass capillary tube. The glass tube was filled with MF in order to form a magnetic fluid cladding layer outside the sandwich structure and then sealed by UV glue to avoid the magnetic fluid from leaking out. Hence, the size of the sensor head was quite small and total dimension of the sensor was about Φ 2mm $\times$ 30mm. It is reported that the length of the sensor can be reduced down to 1.2mm [180].

Light from a broadband light source (amplified spontaneous emission light source, ASE, 1520-1600nm) was launched into the sensor from one single mode fiber and the corresponding transmission spectrum was measured at the other single mode fiber with an optical spectrum analyzer (OSA). The overall configuration was placed amidst a uniform magnetic field which was supplied by an electromagnet (EM4-HVA, LakeShore) and measured by a gaussmeter (Model 425, LakeShore). The magnet had two poles of 100mm in diameter and the air gap between the two poles was fixed at 25mm in the experiment. The uniform cylindrical volume between the two poles of the magnet was about Φ 65mm $\times$ 25mm with a uniformity of 0.05%. The fiber sensor was placed in the center of the uniform field zone. The transverse Hall probe of the gaussmeter was fixed near the sensor head. The external magnetic field was applied perpendicularly to the photonic crystal fiber at the region where the magnetic fluid existed.

The photonic crystal fiber used was a solid core fiber, whose image of scanning electron microscope (SEM) is shown in Figure 5-1(c). The photonic

crystal fiber has typical hexagonal arrangement of air-holes and 4 layers of air-holes surrounding the central solid core. The whole fiber was made up of the same material, pure silica. The diameter of the air-hole is $3.04\mu\text{m}$, which is so small that it is quite easy to be collapsed during the fusion process. The sizes of the core, cladding and mode field are $10\mu\text{m}$, $125\mu\text{m}$ and $7.5\mu\text{m}$, respectively.

A water-based magnetic fluid (EMG605, Ferrotec) with a particle volume concentration of 0.39% was used in the experiment. The nanoparticles in the magnetic fluid are Fe_3O_4 and their nominal sizes are about 10nm. The magnetic fluid used in the experiment, which was a light-brown translucent solution were prepared by the chemical coprecipitation technique [71]. The magnetic susceptibility and the saturation magnetization strength were 2.96 Gs/Oe and 220 Oe, respectively.

The Mach-Zehnder interferometer is actually operated based on modal interference of the photonic crystal fiber with air-holes collapse. As shown in Figure 5-1, the collapsed region of the photonic crystal fiber due to fusion splicing becomes a short section of “glass rod”, hence the single mode condition is no longer satisfied. As light propagates from the single mode fiber to the photonic crystal fiber, the light diffracts and spreads out into the region of “glass rod”. Subsequently, some higher order modes are excited which continue propagating into the photonic crystal fiber in the form of cladding modes. Because the effective refractive indices of the cladding modes and core mode of the photonic crystal fiber are different, a phase difference is accumulated as the light travels along the length of the photonic crystal fiber. As a result, the core mode and cladding modes recombine and interfere at the second collapsed point, subsequently the light after interfering is

guided in the following single mode fiber and monitored by the optical spectrum analyzer. The corresponding transmission spectrum is usually analyzed by the two-mode interference model for simplification [180, 184],

$$T(\lambda) = I_{co}(\lambda) + I_{cl}(\lambda) + 2\sqrt{I_{co}(\lambda)I_{cl}(\lambda)} \cos(2\pi\Delta nL/\lambda) \quad (5-1)$$

where $I_{co}(\lambda)$ and $I_{cl}(\lambda)$ are the intensities of the core mode and first order cladding mode, respectively. Δn is the difference between the effective refractive indices of the core mode and first order cladding mode. L is the length of the photonic crystal fiber; λ is the operating wavelength.

Figure 5-2 shows the transmission spectrum of the Mach-Zehnder interferometer is an approximately sinusoidal function of λ , which indicates that the simplification of two-mode interference model is applicable to this sensor. If the condition $2\pi\Delta nL/\lambda = 2m\pi$ (m is an integer) is fulfilled, the transmission spectrum reaches minimum and a series of transmission dips appear on the transmission spectrum whose wavelengths are given by

$$\lambda_m = \frac{\Delta nL}{m} \quad (5-2)$$

The period of the transmission spectrum (S) can be given by calculating the wavelength spacing between the two adjacent minima,

$$S = \frac{\lambda^2}{\Delta nL} \quad (5-3)$$

S describes the dynamic measurement range of the sensor. Eq.(5-3) shows S is inversely proportional to the length of photonic crystal fiber. Therefore, larger dynamic measurement range can be achieved by reducing the length of photonic crystal fiber (L).

The Mach-Zehnder interferometer is immersed into the magnetic fluid under the external magnetic field to be functionalized as a magnetic field sensor. The cladding modes interact with the magnetic fluid in the form of evanescent field at the outer surface of the photonic crystal fiber, while the core mode is not affected by the dielectric environment of the magnetic fluid. Therefore, as the refractive index of the magnetic fluid is changed with the variation of the magnetic field strength, the effective refractive indices of cladding modes are changed, and in turn the refractive index difference (Δn) as well as the phase difference for interference is changed, too. As a result, the transmission spectrum shifts with the change of the external magnetic field strength. Thus, the magnetic field can be measured by monitoring the shift of the spectrum or the wavelengths of the transmission dips. It is worth noticing that the refractive index of magnetic fluid n_{MF} should be smaller than the refractive index of silica ($n_{silica} = 1.45$) in order to fulfill the condition of total internal reflection. The value of n_{MF} can be controlled by changing the concentration of the magnetic fluid [11, 12].

Figure 5-2 Transmission spectra of the Mach-Zehnder interferometer under different magnetic field strengths

Assuming refractive index is changed from Δn to $\Delta n'$ due to the variation of the external magnetic field strength, the wavelength shift of the transmission dip $\Delta\lambda_m$, which represents the sensitivity of the sensor, can be given by

$$\Delta\lambda_m = \frac{(\Delta n' - \Delta n)L}{m} \quad (5-4)$$

Eq.(5-4) shows that smaller m leads to a larger sensitivity $\Delta\lambda_m$, which is corresponding to the dip at longer wavelength side (i.e. dip 3 shown in Figure 5-2). So we can achieve the highest sensitivity of the sensor by monitoring the dip of the longest wavelength.

5.2.2 Experimental Results and Discussion

The experiment was conducted at the room temperature of 22.7°C. The transmission spectrum of the sensor under zero magnetic field is shown in Figure 5-2 which is indicated by “0.01kOe”. Three transmission dips appeared on the transmission spectrum in the range from 1520nm to 1600nm and the wavelength space between the two adjacent dips was about 24.6nm. The fringe contrast (peak-to-peak ratio) of the transmission spectrum was as high as about 24dB, which was much better than the results of most sensors based on Mach-Zehnder interferometer of sandwich structure [180, 184]. As the magnetic field strength was increased from 0.01kOe to 2.03kOe, the three transmission dips were shifted from 1536.436nm, 1563.168nm and 1587.7nm to 1536.716nm, 1563.712nm, and 1588.436nm, respectively. The corresponding total wavelength shifts were 0.280nm, 0.544nm and 0.736nm, respectively. The fringe contrast (peak-to-peak ratio) remained almost unchanged. It can be seen that the highest sensitivity is obtained from the dip 3.

Thus, the dip 3 was chosen as an example to show the transmission dip shifts gradually to the longer wavelength side with the variation of the external magnetic field strength in details in Figure 5-3. After the external magnetic field strength was removed, the transmission spectrum shifted back to the original position. It shows that the magnetic fluid is superparamagnetic and exhibits no hysteresis effect [10], which means the sensor has a good repeatability.

In order to investigate the sensitivity of the sensor, the relationships between the wavelength shifts of all the three dips and variation of the magnetic field strength are shown in Figure 5-4. It indicates that the variation trends for the three transmission dips are similar as the magnetic field strength increases, which can be fit by modified Langevin function with high R^2 values, but the wavelength shift ranges are different. The dip 3 has the largest wavelength shift range. For each of these three dips, the wavelength shift continues increasing as the magnetic field

strength increases; when the magnetic field strength is smaller than a certain value (saying, $H < 0.3 \text{ kOe}$), the wavelength shift increases linearly and quickly as the increase of the magnetic field strength; when the magnetic field strength is increased larger than a certain value (saying, $H > 0.5 \text{ kOe}$), the wavelength shift tends to get saturated gradually; when the magnetic field strength is between the two certain values (saying, $0.3 \text{ kOe} < H < 0.5 \text{ kOe}$), the wavelength shift is in a period of transition from linear region to saturated region.

Linear fit method is applied to the linear region of all the three curves. The achieved corresponding sensitivities for the dip 1, dip 2 and dip 3 are 1.012 pm/Oe , 1.927 pm/Oe and 2.367 pm/Oe , respectively. The dip 3, at the longest wavelength, has the best sensitivity, which is coincident as the theory predicts. For the dip 3, the sensitivity is twice better than the result of sensor based on Fabry-Perot interferometer which was about 1.25 pm/Oe [115] and one order of magnitude better

than the result of the magnetic field sensor based on etched fiber Bragg grating which was about 0.344pm/Oe [153]. If the resolution limit of the optical spectrum analyzer (10pm) is considered, the corresponding resolutions for the dip1, dip 2 and dip 3 are 9.88Oe, 5.19Oe and 4.22Oe, respectively.

Another distinguished advantage of photonic crystal fiber over conventional fiber is the ultralow temperature coefficient because it is made up of identity material, fused silica, thus the photonic crystal fiber can avoid the problems caused by the different thermal expansion coefficients existing in the core and cladding area of the conventional fiber. The temperature stability of the sensor was tested in the experiment, too. The overall sensor was placed into a temperature-controlled oven. The temperature was measured by a digital thermometer with an accuracy of $\pm 0.5\%$. The sensor was heated in the oven and then the corresponding transmission spectrum was measured after the temperature was stable. The wavelength shift was recorded as the temperature increased from 30°C to 100°C with an interval of 5°C and the result is shown in Figure 5-5. During the process of the increase of the temperature, the wavelength shift increases linearly from 1587.702nm to 1587.933nm, totally about 0.231nm to the longer wavelength side. A linear fit is applied to the data with a high R^2 value of 0.9976, which means the temperature dependence of the sensor has a highly linear relationship. The linear fit function of the data can be used to compensate wavelength shift deviation caused by the environmental temperature. The temperature dependent coefficient of the sensor is calculated to be 3.2pm/°C, which is about 3 orders of magnitude better than the result of conventional fiber which is about 1nm/°C [120]. However, the temperature coefficient is comparable to the sensitivity of the magnetic field sensor, if the

environmental temperature variation range larger than 1°C, it is better that the temperature compensation is applied for the sensing measurement.

Figure 5-5 Relationship between wavelength shift of dip 3 and variation of magnetic field strength in the temperature range from 30 °C to 100°C

5.2.3 Conclusion

In conclusion, a magnetic field fiber sensor based on the Mach-Zehnder interferometer and the magnetic fluid is proposed and demonstrated. The modal interference phenomenon is achieved by using the two collapsed points of air-hole cladding on the length of the photonic crystal fiber to form the Mach-Zehnder interferometer, whose evanescent field is sensitive to the ambient dielectric constant and refractive index in the environment. Moreover, the magnetic fluid is such a nanostructure function material that its dielectric constant and refractive index is tunable under external magnetic field. Hence, the proposed magnetic field fiber sensor is configured by combining Mach-Zehnder interferometer and tunable refractive index property of magnetic fluid. Theoretical analysis of the operating principle indicates that higher sensitivity can be achieved by using lower order

interference fringe of the spectrum and the experimental results support this conclusion. The achieved sensitivity and resolution are 2.367pm/Oe and 4.22 Oe, respectively. The ultralow temperature dependence coefficient of the sensor is 3.2pm/°C. The sensor structure is simple, robust and easy for manufacturing. Although the splicing points of PCF may slightly differ from time to time, the modal interference phenomenon is repeatable; hence the sensing performance is not affected. The sensor can also find some potential applications such as magneto-optical modulation, magneto-optical filter and so on.

In this Section, we have mainly discussed the magnetic field sensor based on an evanescent-field-type refractive index sensor. Although the sensor can work as expected, the sensitivity result is not as good as the results of the ones as shown in Chapter 4. In next Section, we will discuss another unique property of PCF, saying the photonic bandgap shift effect. We will combine the photonic bandgap effect of PCF and the tunable refractive index property of MF to realize a magnetic field sensor with dramatically enhanced sensitivity.

5.3 Photonic Bandgap Effect of Photonic Crystal Fiber for Sensing Measurement¹¹

In Section 5.2, we have discussed the evanescent field property of PCF with air-holes collapse and it is combined with MF to realize a magnetic field sensor. In

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this Section, we will investigate another important property of PCF, saying the fillable air-hole structure of PCFs. Actually, among the literatures, most reported PCF sensors are based on the photonic bandgap effect of PCF. As reviewed in Section 2.2, the photonic bandgap effect of PCF for sensing purpose can be realized by simply filling high refractive-index liquid ($n > 1.45$) into the air-holes of solid core index guiding PCF. The bandgap will shift with the variation of the refractive index of the liquid filled in due to various effects such as electro-optical effect, thermo-optical effect, magneto-optical effect, photoelastic effect and so on. The sensitivities of the sensors based on the photonic bandgap effect are about 10000-15000nm/RIU, which is 2-3 orders of magnitude better than the other kind of refractive index sensors [107, 185-188]. The flexible air-hole structures of PCFs and the ultrahigh sensitivity to refractive index make them excellent candidate as a platform for liquid filled optical devices, especially for optical sensors of refractive-index measurement nature [189]. MF is a liquid with magnetically controllable refractive index, so it can be filled into the PCF to realize a magnetic field sensor based on the photonic bandgap effect. In this Section, we will first fill the solid core index guiding PCF with a standard refractive index oil to realize a temperature sensor. The refractive index of the standard refractive index oil is tuned through thermo-optical effect. We observe the evolution of the photonic bandgap in PCF and find the conditions for achieving a higher sensitivity through this temperature sensing structure. In the next Section, we will fill the MF in the PCF to realize a magnetic field sensor.

5.3.1 Principle of the Sensing Configuration

PCF is a kind of fiber based on the properties of photonic crystal, whose significant difference from traditional fiber is the introduction of periodic air-hole structures into the cross section of the fiber. If the refractive index of the core area is higher than the average refractive index of air-hole cladding (e.g. solid core PCF), its guiding mechanism is total internal reflection and it is classified as index guiding fiber. If the refractive index of the core area is lower than the average refractive index of air-hole cladding (e.g. hollow core PCF), its guiding mechanism is photonic bandgap effect and it is classified as photonic bandgap fiber. The two classes of PCFs can be converted into each other by filling liquid with high refractive index into the air-hole structures. The conversion map between the two classes of PCFs is shown in Figure 5-6.

Figure 5-6 Conversion between the index guiding fiber and photonic bandgap fiber by filling liquid of high refractive index into the air-holes of the PCF

According to the conversion map in Figure 5-6, there are two methods to realize a liquid filled photonic bandgap fiber. One method is filling the liquid into the air-holes of index guiding fiber to realize a photonic bandgap fiber. The only requirement is the refractive index of liquid filled in should be higher than the refractive index of fiber material, pure silica ($n_s \approx 1.45$) [189, 190]. After filling the liquid with high refractive index into the air-holes of an index guiding PCF, the

average refractive index of cladding becomes higher than the refractive index of the core area, so the liquid filled photonic bandgap fiber can be realized. Usually, the liquid filled photonic bandgap fiber realized through this method has a solid core. The light propagates in the solid core and do not interact with the liquid directly, so the transmission loss due to absorption is relative small.

Another method to realize a liquid filled photonic bandgap fiber is filling the liquid into the air-hole structures of a photonic bandgap fiber. The requirement is the refractive index of liquid filled in should be lower than the refractive index of fiber material, pure silica. In this case, after filling the liquid with low refractive index into the air-holes of a photonic bandgap fiber, the average refractive index of cladding is still higher than the refractive index of the core area, so the liquid filled photonic bandgap fiber can be realized. Usually, the liquid filled photonic bandgap fiber realized through this method has a hollow core. The light propagates in the liquid filled core and interact with the liquid directly, so the transmission loss due to absorption is relative large.

As discussed in Chapter 4, the absorption coefficient of MF is huge, so usually the light cannot propagate longer than 0.1mm in the MF. Since we want to fill MF into the air-holes to realize the liquid filled photonic bandgap fiber, the first method is a better choice.

The photonic bandgap fiber exhibits a series of bands interrupted in wavelength, which depend on the refractive index of the liquid filled in. Therefore sensing measurement can be carried out by monitoring the spectral shift of the bands. In this experiment, the refractive index of the liquid filled in is tuned thermo-optical effect. In other words, the refractive index of the liquid filled in is tuned by the environmental temperature.

According to the scaling law which deduced from scalar wave equation, the wavelength of the transmission bands can be given by [191]

$$\frac{\lambda_t}{\lambda_0} = \sqrt{\frac{n_t^2 - n_s^2}{n_0^2 - n_s^2}} \quad (5-5)$$

where λ_0 is the original edge wavelength of the bandgap; λ_t is the final wavelength of the same band edge after the change of the temperature. n_s is the refractive index of the fiber material, pure silica; n_0 is the initial refractive index of the liquid filled in before the change of the temperature; n_t is the final refractive index of the liquid filled in after the change of the temperature. Usually, the refractive index of the liquid is proportional to the environmental temperature, which is given by [192]

$$n_t = n_0 + k\Delta T \quad (5-6)$$

where k is the temperature coefficient of the liquid filled in; ΔT is the change of the temperature. Substitute Eq.(5-6) into Eq.(5-5), the sensitivity $\Delta\lambda$, which is described by the change of the edge wavelength $\Delta\lambda = \lambda_t - \lambda_0$, can be given by

$$\frac{\Delta\lambda}{\lambda_0} = \sqrt{\frac{(n_0 + k\Delta T)^2 - n_s^2}{n_0^2 - n_s^2}} - 1 \quad (5-7)$$

In order to observe the variation trend of the edge wavelength of the bandgap with the refractive index of the liquid filled in or the environmental temperature, a simulation is carried out. The result is in Figure 5-7. The refractive index of the liquid filled in (n_0) should be larger than the refractive index of pure silica ($n_s \approx 1.45$), hence the range of n_0 is given as 1.46-1.60. The variation range of the temperature is 0-20 °C. The temperature coefficient of the liquid is $k = -0.0004 \text{ RIU/}^\circ\text{C}$. The original edge wavelength is $\lambda_0 = 1550 \text{ nm}$.

Figure 5-7 The dependence of the edge wavelength shift on the temperature and the refractive index of liquid filled in

Figure 5-7 shows that the edge wavelength of the bandgap shifts to the shorter wavelength side as the temperature increases (i.e. as the refractive index of the liquid filled in decreases). The larger the temperature, the higher the sensitivity. Meanwhile, the lower the initial refractive index of the liquid filled in, the higher the sensitivity. However, in order to realize the photonic bandgap fiber, the following condition should be fulfilled.

$$n_0 + k\Delta T > n_s \quad (5-8)$$

ΔT is the variation of the temperature, which also represents the dynamic measurement range since k is negative. Therefore, in order to obtain both as high a sensitivity as possible and as large a dynamic measurement range as possible, we need to do some optimization on the initial refractive index of liquid filled in according to the practical situation.

5.3.2 Experimental Results and Discussion

The schematic diagram of the experimental setup is shown in Figure 5-8. A supercontinuum light source and an OSA were used to monitor the transmission spectrum of the liquid filled PCF. The liquid filled PCF was heated in an oven and calibrated with a digital thermometer.

The PCF used in the experiment was a solid-core index guiding fiber, LMA-10 (Inset in Figure 5-8). Four hexagonally arranged air-holes layers surround the solid core in the cross Section of the PCF. The core diameter, air-hole diameter and pitch are $5.9\mu\text{m}$, $3.04\mu\text{m}$ and $6.26\mu\text{m}$, respectively. The fiber material is pure silica, and its refractive index is about 1.45.

The temperature sensitive liquid filled in the PCF is a kind of standard refractive index oil (Cargille Labs). At room temperature, its refractive index is 1.500. The temperature coefficient of the refractive index oil is $-0.000401\text{RIU}/^\circ\text{C}$ whilst the temperature coefficient of pure silica is $8.6 \times 10^{-6} \text{ RIU}/^\circ\text{C}$.

The standard refractive index oil was infiltrated into the air-holes of a 15-mm-length PCF solely by means of the physical capillary effect. It took about 20 minutes to fill the whole length of PCF. The PCF was spliced in between two sections of single mode fiber for measurement convenience by a common splicer. The total splicing loss for the two splicing points was about 3dB. The spectral range of the supercontinuum light source is 500nm-1800nm (NKT, photonics A/S). The measurement range of OSA is 600nm-1700nm (AQ6370).

The temperature in the oven was increased from 22.4°C to 279.3°C and the transmission spectra was recorded with an interval of 3-5°C. In order to show the spectral shift clearly, all the results are plotted in 5 groups in Figure 5-9.

Figure 5-9 Transmission spectra of the liquid filled photonic bandgap fiber under different temperatures

As shown in Figure 5-9(a), there are 4 main transmission bands on the transmission spectrum at the room temperature 22.4°C whose range are 630nm-720nm (Band 1), 890nm-1270nm (Band 2), 1270nm-1520nm (Band 3) and 1520nm-1700nm (Band 4). It shows that the index guiding fiber is successfully converted into photonic bandgap fiber by filling the standard refractive index oil with refractive index value of 1.500. Out of these 4 transmission bands, Band 2 is the widest (about 380nm) and most intact, which has a very sharp right edge with a high out-of-noise ratio of 35dB. In the experiment, Band 2 is observed in the process of increasing temperature. Band 1 is in the visible range and its transmission loss is the lowest. Band 3 suffers from big transmission loss and it can be viewed as reject band. Band 4 covers 1550nm band, which is most commonly used in optical fiber communication.

During the process of the temperature is increased from 20°C to 100°C, the refractive index of the liquid remains higher than the fiber material (i.e. $n_l > 1.45$), therefore the PCF is a photonic bandgap fiber. The bandgaps shift to the shorter wavelength side and become narrower as the temperature increases. Band 1 shifts to the left side and gradually out of the measurement range of the measurement devices. The boundary of Band 3 and Band 4 is gradually vague and then they merge into one band. Band 2 remains intact during the whole process, which continues shifting to the left side and becomes narrower.

When the temperature is increased to 100°C, all the transmission bands disappear and the spectrum becomes a straight line and the transmission loss of the liquid PCF is up to 60dB. This is because the refractive index of the liquid filled in has decreased to around 1.45 according Eq.(5-6), which is close and even lower to

the refractive index of fiber material, then the liquid filled PCF becomes a “glass rod” without refractive index contrast between its core and cladding area. Therefore, the “glass rod” cannot fulfill the conditions of neither the total internal reflection nor the photonic bandgap effect, so PCF cannot deliver light at all. This temperature (100.6°C) can be viewed as a critical temperature or turning point that the liquid filled PCF is converted from photonic bandgap fiber into index guiding fiber. During the process of the temperature is increased from 100 °C to 280 °C, transmission loss of the liquid filled PCF, which is an index guiding fiber, becomes smaller and the power level has increased about 20dB. Hence, this liquid filled PCF may have the potential to be developed as a variable attenuator.

In the temperature range of 20°C-80°C, the right edge wavelength of Band 2 at the -50dBm was recorded in Figure 5-10. Liner fit method is applied to the data. A temperature sensitivity of 9.3575nm/°C with a high R^2 value is achieved. This sensitivity result is 3 orders of magnitude better than the one of common fiber Bragg grating (FBG) [193]; is 1-2 orders of magnitude better than the one of modified long period grating (LPG) [194-196]; is 1.5-9 times better than the one of the sensors based on OFSI [168].

As predicted by Eq.(5-6) and Figure 5-7, the sensitivity of this liquid filled PCF also depends on the refractive index of the liquid. Therefore, we split the data into three sections, which are 20°C-40°C, 40°C-60°C and 60°C-90°C, respectively. The linear fit method is applied to the each section, which is shown in Figure 5-11. The achieved sensitivities are 7.4724nm/°C, 9.1545 nm/°C and 10.927 nm/°C respectively. The results show that the lower the refractive index of the liquid, the more sensitive the sensor to the change of the refractive index. This experimental

result supports the predictions by Eq.(5-6) and Figure 5-7. However, low initial refractive index of the liquid means small dynamic range of the sensor with a negative thermo-optical coefficient. This point needs to be noticed in practical applications.

Figure 5-10 Edge wavelength of Band 2 under different temperatures

Figure 5-11 Sensitivity of the liquid filled PCF under different refractive indices

During the process of increasing temperature, Band 1 and Band 2 will in turn cover the visible band of light. Since the light source is white light, the liquid filled PCF filters out different colour light during the process. The colour and the intensity of the light are all changing gradually during the process (Figure 5-12).

5.3.3 Conclusion

In conclusion, the photonic bandgap fiber can be realized by filling the air-holes of an index guiding PCF with liquid of high refractive index (>1.45). In this experiment, the refractive index of the liquid filled in is tuned through thermo-optical effect. The bandgaps on the transmission spectrum shift with the refractive index of the liquid filled in. The complete evolution of the liquid filled in PCF from photonic bandgap fiber to index guiding fiber is demonstrated in this experiment. The results suggest that higher sensitivity of the liquid filled in PCF can be achieved at lower refractive index, but the refractive index needs to be remain higher than 1.45 all the time.

In next Section, on the basis of the conclusions drawn from this Section, we will fill the MF into the PCF to realize a magnetic field sensor.

5.4 Development of a Magnetic Field Sensor Based on Bandgap Effect of Photonic Crystal Fiber¹²

In Section 5.3, we have demonstrated the tuning of the photonic bandgaps of a liquid filled PCF with thermo-optical effect of the liquid filled in. In this Section, we will fill MF into the air-holes of the PCF to demonstrate the tuning of the photonic bandgap through the magneto-optical effect of MF.

In the literatures, several magnetic field sensors based on the MF filled PCF have already been reported. For instance, Harneet realized a magnetic field sensor by infiltrating MF into the air-holes of a PM-PCF with a sensitivity of 24.2pm/Oe [173]. Alessandro presented a magnetic field controlled phase-shifted fiber grating by selectively filling MF into the air-holes in the cladding of a hollow core PCF [197]. However, it is well known that the significant advantage of PCF for sensing application is the photonic bandgap shift effect, which can improve the sensitivity dramatically. There is not any demonstration of photonic bandgap effect by infiltrating PCF with MF for magnetic field sensing. The main challenges are the refractive-index value of MF does not fulfill the condition of photonic bandgap effect and the absorption loss of MF is too huge to transmit light in a length longer than 100 microns. We will focus on solving these problems in this Section.

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5.4.1 Principle of the Sensing Configuration

As reviewed in Section 2.1, MF is a stable translucent superparamagnetic colloidal suspension of ferromagnetic nanoparticles in a suitable liquid carrier. The ultra-fine nanoparticles (for example, Fe_3O_4 or Fe_2O_3) whose nominal diameter is smaller than 10nm, is fabricated by chemical coprecipitation method [71]. In order to disperse the solid-state nanoparticles in an appropriate solvent uniformly, surface modification with compatible surfactant is necessary to be applied on the nanoparticles, which can prevent the nanoparticles from magnetic clumping or agglomerating. Oleic acid is the most commonly used surfactant, while water-based MF is the most commonly used in the magneto-optical applications. Under zero magnetic field, the nanoparticles is dispersed homogeneously in the solvent, which is a mono-dispersion state. When the MF is subjected to a magnetic field, the nanoparticles begin to agglomerate to form magnetic columns and a phase separation occurs between the solid nanoparticles and liquid solvent [56]. Meanwhile the magnetic columns tend to align with the direction of magnetic field [15]. This change of the dispersion state of the nanoparticles subsequently affects the effective dielectric constant or refractive index of the MF. The initial refractive index of MF under zero magnetic field is dependent on the concentration of MF, whose value increases from the intrinsic refractive index corresponding to the liquid solvent linearly and continuously with the particle concentration of MF [11]. Under the external magnetic field, the refractive index of the MF increases slightly as the magnetic field strength is increased, whose variation trend follows a Langevin function. The variation range of the refractive index of MF also depends on the concentration of MF. The higher the concentration of MF, the larger the variation range of refractive index [12]. The magnetic field induced refractive index change of MF can be used for magnetic field sensing measurement in a suitable

refractometer structure. In this experiment, the PCF was chosen as a highly sensitive platform.

As discussed in the Section 5.3, PCF can be generally divided into two main classes, one is index guiding fiber (e.g. solid core PCF), which is operated on the traditional total internal reflection and the other is photonic bandgap fiber (e.g. hollow core PCF), which is operated on photonic bandgap effect. The index guiding fiber can be converted into photonic bandgap fiber by filling liquid into the air-hole structure. The only requirement is the refractive index of liquid filled in should be higher than the refractive index of fiber material, pure silica ($n_s \approx 1.45$) [189, 190]. Photonic bandgap fiber exhibits a series of bands interrupted in wavelength, which depend on the refractive index of the liquid filled in. Therefore sensing measurement can be carried out by monitoring the bands shift. The PCF used in the experiment was a solid-core IGF, LMA-10 (Figure 2). Four hexagonally arranged air-holes layers surround the solid core in the cross section of the PCF. The core diameter, air-hole diameter and pitch are $5.9\mu\text{m}$, $3.04\mu\text{m}$ and $6.26\mu\text{m}$, respectively.

MF with refractive index higher than 1.45 was prepared to convert the index guiding fiber into photonic bandgap fiber. Generally, the refractive index of water-based MF with a

moderate concentration is lower than 1.45 since the refractive index of water is only 1.333 [11]. Hence, we chose another solvent with a higher refractive index value, toluene, whose refractive index at room temperature is 1.497. In order to obtain a good sensitivity, the change of the refractive index of MF under external magnetic field should be as large as possible, so the MF with a high concentration is preferred. In the experiment, 10mg dry ferromagnetic nanoparticles with fatty acid coating (EMG1200 from Ferrotech) were dispersed in 5.3g toluene and then an ultra sound treatment was applied. After the treatment, we got a translucent uniform light brown MF with a mass concentration of 0.18%. Then the MF was infiltrated into the air-holes of a 20-mm-length PCF solely by means of physical capillary effect. It took less than an hour to fill the whole length of the PCF.

We numerically simulated effective refractive-index maps on the basis of the given conditions to check whether a bandgap can be supported in this MF filled PCF. The refractive index of MF was set to be 1.497. The plane-wave-expansion method was used to perform the simulation. As shown in Figure 5-14(a), the light grey areas represent the supported bandgap modes. The transverse mode profiles of the MF filled PCF at different wavelengths were also computed. For example, Figure 5-14(b) is the transverse profile at 900nm and the light can be well confined in the core area, which means a bandgap exists at this wavelength; while Figure 5-14(c) is the transverse mode profile at 1700nm and the light radiates into the liquid-filled cladding, which means a reject band exists at this wavelength.

5.4.2 Experimental Results and Discussion

The experimental setup is shown in Figure 5-13. The MF filled PCF was spliced in between two sections of single mode fiber by a common splicer for measurement convenience. The total splicing loss for the two splicing points was about 6dB. A supercontinuum light source (500-1800nm, NKT photonics A/S) and an optical spectrum analyzer (OSA, 600-1700nm, AQ6370) were employed to monitor the transmission spectrum of the PCF. The magnetic field was generated with a Helmholtz coil (YL4020) and calibrated with a Gaussmeter. The MF filled PCF was placed in the uniform area of the Helmholtz coil and its length direction was aligned parallelly with the magnetic field direction. The experiment was conducted at the room temperature of 23.7°C.

The transmission spectra of the MF filled PCF under different magnetic field strengths are shown in Figure 5-15. The blue curve indicated by “0 Oe” is the transmission spectrum of the magnetic field sensor under zero magnetic field. Four distinct pass bands appear on the spectrum from 600nm to 1700nm with assigned number of band 1 to band 4, which shows that the original index guiding fiber is converted to photonic bandgap fiber by filling the MF into the air-holes. Band 2 is the widest (about 200nm) and most intact. Particularly, band 2 has a very sharp right edge with a high out-of-noise ratio of 35dB. Therefore, band 2 is ideal for monitoring the bandgap shift of the spectrum. As the magnetic field strength is increased from 0 Oe to 225 Oe with an interval of 15 Oe, band 2 becomes wider and its right edge shifts to the longer wavelength side from 1041nm to 1105nm totally 64nm.

The bandgap shift (edge shift) during the change of the magnetic field strength was recorded in order to evaluate the sensitivity of the sensor. The wavelength of the right edge

plotted in Figure 5-16. Figure 5-16 shows that, during the process of increasing the magnetic field strength, when it is lower than certain strength (saying $H < 30\text{Oe}$), the edge wavelength shifts quickly and linearly; when it is higher than certain strength (saying $H > 100\text{Oe}$), the edge wavelength shift tends to be saturated. The curve is fit by modified Langevin function with a high goodness-of-fit coefficient R^2 value [198]. Because MF is a superparamagnetic material which means MF always returns to its original state when the applied magnetic field is removed, this proposed sensor also showed a good repeatability [62, 199]. Linear fit method is also applied to the linear region of the curve and a sensitivity of 1.56nm/Oe is achieved. In the literatures, Hu reported the magnetic field sensor based on Fabry-Perot interferometer with a sensitivity of 1.5pm/Oe [115]; Liu proposed a filter based on long period grating with tunable sensitivity of 4.4pm/Oe ; the magnetic field sensor based on Sagnac interferometer and modal interference were also carried out in our previous work with sensitivities of 16.7pm/Oe [73] and 2.367pm/Oe , respectively; Thakur filled the polarization maintaining PCF with MF and achieved a sensitivity of 24.2pm/Oe ; However, our experimental result is 1.56nm/Oe , which is 2-3 orders of magnitude better than these reported results.

Based on the resolution limit of the OSA at 10pm , a resolution of 0.0064Oe can be calculated approximately with the assumptions such as signal to noise ratio of the light source and thermal noise of the equipment as indicated in reference [200] not affecting the sensor's resolution. This resolution is an ideal resolution by only taking account of the resolution limit of the OSA and the sensor's sensitivity. This would give an overestimation of sensor's performance, but it is given for comparison of the performance of the proposed sensor in a way that is familiar to most readers.

Figure 5-16 Variation trend of the edge wavelength vs the magnetic field strength

It is worth noticing that, though the MF with higher refractive index can be achieved by increasing the concentration of the water-based MF, it is not suitable for filling into the air-holes of PCF to perform this sensing measurement, because the nanoparticles contained within the high concentration liquid tend to agglomerate and adhere to the inner wall of air-holes irreversibly, which will fail the measurement. Therefore, MF with a higher refractive-index solvent is highly recommended in this sensing scheme.

5.4.3 Conclusion

In conclusion, a magnetic field sensor based on the tunable bandgap effect of the MF filled PCF is theoretically analyzed and experimentally demonstrated. The bandgap is tuned through the tunable refractive index property of MF. The solid core index guiding fiber is converted to photonic bandgap fiber by filling the air-holes of the PCF with MF, whose refractive index is controllable with external magnetic field. The key to this sensor is the preparation of the toluene-based MF with a higher refractive index (higher than 1.45). The achieved sensitivity and resolution of the sensor are 1.56nm/Oe and 0.0064Oe, respectively,

which are 2-3 orders of magnitude better than the reported MF-based sensor. The sensor also has the merits of simple fabrication, low cost and miniature structure.

5.5 Chapter Summary

In this Chapter, we have developed two kinds of magnetic field sensors by combining the tunable refractive index property of MF and the unique properties of PCF. Either kind of these two magnetic field sensors has its own special requirement for the refractive index of MF.

The first kind of magnetic field sensor based on the evanescent field of the PCF with air-holes collapse, which requires the refractive index of the MF should be lower than the fiber material (<1.45). In this sensor, the air-holes of PCF are collapsed and become a “glass rod”. An evanescent field is generated and multi modes are excited. Two cascaded regions of PCFs air-holes collapse constitute a Mach-Zehnder interferometer which makes use of the modal interference. The MF with tunable refractive index serves as the outing cladding layer of the collapsed region to maintain the condition of total internal reflection for the “glass rod”. As other evanescent field sensors in the literatures, the sensitivity of this magnetic field sensor is in an average level.

The second kind of magnetic field sensor based on the phonic bandgap effect of the MF filled PCF, which requires the refractive index of the MF should be higher than the fiber material (>1.45). First, the whole evolution of the liquid filled PCF from index guiding fiber to photonic bandgap fiber is demonstrated by tuning the refractive index of the liquid filled in through the thermal optical effect. In this sensing configuration, the PCF is filled with MF of higher refractive index so that

the solid-core index-guiding fiber is converted into a photonic bandgap fiber. As well known, the photonic bandgap effect of liquid filled fiber is extremely sensitive to the refractive index of the liquid filled in, so the sensitivity of this magnetic field sensor is 2-3 orders of magnitude better than the reported results of the other magmatic field sensors based on MF in the literatures.

Both kinds of magnetic field sensors require some extent of design of the refractive index of MF. Meanwhile, the sensitivities of the sensors may depend on the types of the nanoparticles in the MF, for example, MnFe_2O_4 or nanorod, so it can be further explored in the future work.

Chapter 6 Conclusions and Future works

6.1 Summary of the Investigation

In the previous Chapters, we have investigated the magneto-optical properties of MF, especially the linear birefringence effect and tunable refractive index effect, and applied them in the applications of MF-based magnetic field sensors and magneto-optical modulators. As for the MF-based magnetic field sensors, the efforts are devoted to improve the sensitivities; while as for the MF-based magneto-optical modulators, the efforts are devoted to achieve high extinction ratios. The satisfactory experimental results of these MF-based applications show that MF is a promising magneto-optical material and has high potentials to be applied in simple, flexible and high-performance fiber optics devices. Besides, taking full advantages of the optical fiber interferometry as a tool (i.e. optical fiber Sagnac interferometer), we have also observed the laser self-induced tunable birefringence phenomenon of MF. This optical fiber Sagnac interferometric configuration is a good potential candidate to replace the traditional observation and measurement method for the MF. In this Chapter, we will summarize the works which have been done and suggest some future research works.

The first work (Chapter 3) is aimed to find a suitable fiber optics configuration as a tool for applying the magneto-optical effects of MF, especially the magnetically controllable birefringence effect of MF. MF has both the linear

birefringence effect and the circular birefringence effect, but the absorption coefficient is quite large. After comparing the advantages and the disadvantages of various optical fiber interferometric configurations, the OFSI is chosen as a better choice, which is sensitive to birefringence effect but immune to the huge transmission loss. We have investigated how the linear birefringence effect work in the OFSI by a transverse force sensor and how the circular birefringence effect work in the OFSI by a twist sensor. The optical fiber Sagnac interferometric configuration used in this experiment is very simple, but has laid the foundation for the works in the next Chapter.

The second work (Chapter 4) is aimed to develop the magneto-optical devices based on the birefringence effect of MF. A high-birefringence-fiber assisted optical fiber Sagnac interferometric configuration, which is a Loyt-Sagnac interferometer in essence, is proposed on the basis of the works in Chapter 3. In the Loyt-Sagnac interferometer, the high birefringence fiber provides an initial constant phase difference for the fixed bias purpose, whilst the thin MF film provides the variable phase difference due to the change of the birefringence effect for measurement. A magnetic field sensor based on this Loyt-Sagnac interferometer is successfully demonstrated with a sensitivity of 16.7pm/Oe, which is 1-2 orders of magnitude better than the results in the literatures. We find that, the sensitivity of this sensing configuration can be further improved by reducing the length of the high birefringence fiber used within the Sagnac loop. The length of the high birefringence fiber used in the experiment is 2cm and the best sensitivity result achieved in the experiment is 592.8pm/Oe, which is 2-3 orders of magnitude better than the reported results. The dynamic performance of this MF-based OFSI is also

tested for demonstrating the light modulation. As predicted in Chapter 2, it is easier to achieve high extinction ratio with the optical fiber Sagnac interferometric configuration. The best extinction ratio of this OFSI-based magneto-optical modulator achieved in the experiment is 19.5dB, while most reported results are less than 1dB. Through further analysis, we find that if some conditions are fulfilled, the extinction ratio can be further improved. Then, we have carried out a magneto-optical modulator based on polarimetric configuration, which is similar to the optical fiber Sagnac interferometric configuration, and the achieved extinction ratio is 38dB. Meanwhile, we have observed the phenomenon of laser self-induced tunable birefringence effect by means of this optical fiber polarimetric configuration. Therefore, the high-birefringence-fiber assisted optical fiber Sagnac interferometric configuration and polarimeter configuration can be used as a good flexible tool for observing the phenomenon related to the birefringence effect of MF.

The third work is aimed to develop the magnetic field sensors based on the tunable refractive index effect of MF. The newly emerged fiber, photonic crystal fiber, is chosen as the platform. We have developed two kinds of magnetic field sensors based on the tunable refractive index property of MF. One is applicable to the case that the refractive index of MF is lower than the one of fiber material (i.e. $n_{MF} < 1.45$) whilst the other one is applicable to the case that the refractive index of MF is higher than the one of fiber material (i.e. $n_{MF} > 1.45$). The principle of the former one is on the basis of evanescent field of PCF with air-holes collapse. Two cascaded air-hole collapsed regions on PCFs form a Mach-Zehnder interferometer. The light interacts with MF in the form of evanescent field and carries on the information of external magnetic field. The sensitivity of 2.367pm/Oe was achieved.

The principle of the latter magnetic field sensor is based on the photonic bandgap effect of the photonic crystal fiber. The MF with higher refractive index ($n_{MF} > 1.45$) is filled into the air-holes of photonic crystal fiber and converted the photonic crystal fiber from index guiding fiber into photonic bandgap fiber. The photonic bandgap fiber exhibits a series of interrupted bands in wavelength, which depend on the refractive index of the liquid filled in. Therefore sensing measurement can be carried out by monitoring the bands shift. The achieved sensitivity is 1.56nm/Oe, which is 3 orders of magnitude better than the reported results.

The achieved results of the works in this thesis are listed in Table 6-1 for comparison.

Table 6-1 Achieved results of proposed magnetic field sensors and magneto-optical modulators

Applications	Configurations	Properties of MF	Principles	Results Sensitivities/ERs
Magnetic field sensors	SI	Birefringence	Interference	59.2pm/Oe
	MZI	Refractive index	Evanescent field	2.367pm/Oe
	Transmission	Refractive index	Bandgap effect	1.56nm/Oe
Magneto-optical modulators	SI	Birefringence	Interference	19.5dB
	Polarimeter	Birefringence	Interference	38dB

The combination of the magneto-optical properties of MF and the fiber optics opens up a new area of research. Since the traditional magneto-optical materials are all solid materials, the liquid MF possesses some unique merits for fiber optics

applications. Especially, the newly emerged photonic crystal fibers with flexible air-hole structures offer even more opportunities for the MF-based fiber optics devices. As the development of optical fiber technology, more and more MF-based fiber optics devices will come to fruition.

6.2 Suggestion for Future Works

Since the research topic in this thesis is the combination of magneto-optical properties of MF and the fiber optics technology, there may be two main directions for the future research works. One effort can be devoted to deepen the understanding of the physical origin of the magneto-optical properties of MF in order to obtain better performance, which is related to MF itself; The other effort can be devoted to apply MF in more kinds of PCFs. Some potential future research works are listed as follows.

6.2.1 Improvement of Magneto-Optical Properties of Magnetic

Fluid

In the MF-based devices, we always expect the ranges of the change of the magneto-optical properties (e.g. tunable refractive index effect or birefringence effect) are as large as possible. For example, according to Eq.(4-16), the sensitivity of the sensor is proportional to the change of the birefringence of MF. It means the larger the change of the range of the birefringence effect, the higher the sensitivity. Therefore, how to increase the variation range of the birefringence is a topic that is worth further exploring from the perspectives of physics and especially material science. For example, as reviewed in Chapter 2, orientation theory is one of the theories that explains the origin of the birefringence of the MF [64]. Orientation

theory considers the nonspherical nanoparticles (but close to sphere) reorient along the external magnetic field, which is responsible for the birefringence effect. Therefore, we can use nanoparticles with large nonsphericity to realize the MF with high birefringence effect. Nanorods are such kinds of materials that fulfill this condition. Recently, with the development of nanotechnology, various magnetic nanorods have been reported [201, 202] which have a great potential to be utilized in the area of optics and fiber optics. Another clue can be followed is that MF containing different ferric nanoparticles may exhibit higher change of birefringence under external magnetic field. For example, it was reported that the MF containing MnFe_2O_4 has a larger change of refractive index than the MF containing Fe_3O_4 , so the MF containing MnFe_2O_4 may exhibit a larger range of the change of birefringence [11].

6.2.2 Development of All Fiber Devices Based on MF filled

Photonic Crystal Fiber

The magnetic field sensors and magneto-optical modulators proposed in Chapter 4 are based on the birefringence effect of MF. The MF inserted in the optical fiber Sagnac interferometric configuration or the polarimetric configuration is in the form of film with the assistance of several free-space optical fiber components like optical fiber collimators. An extra insertion loss may be introduced when the free-space components are misaligned. Besides, the accurate alignment of the free-space components is vulnerable to mechanical vibration. A possible solution to this problem is the development of all fiber devices. As reviewed in Chapter 2, the flexible air-hole structures of PCFs make them an excellent platform

for MF. For example, in the configurations in Section 4.2, the traditional polarization maintaining fiber (Figure 6-1(a)) can be replaced by polarization maintaining PCF (Figure 6-1(b)) and the MF can be filled into the air-holes of PCF directly. After replacement, the operating principle remains the same. Therefore, the performance of the devices can be optimized according to the conclusions drawn in Section 4.5.

The proposed magnetic field sensor in Section 5.3 is based on a solid core PCF. The light propagates in the solid core and cannot interact directly with the MF in the air-holes of PCF. Therefore, the MF can be filled into the hollow core PCF (if the transmission loss of MF can be reduced) so that light propagates directly in the MF filled core and interact directly with the MF. Besides, various designs of hollow core polarization maintaining PCF are also reported [203, 204], which can be served as the platform. It can be expected that the sensitivity based on this MF-filled hollow core PCF will be further enhanced.

6.2.3 Development of MF-Based Devices by Combing Magnetic

Fluid and Fiber Grating

Fiber grating is a type fiber device, which is fabricated by imprinting periodic distribution of refractive index into the core area of the fiber. The fiber grating reflects one or a series of specific wavelength of the light spectrum, which are sensitive to the dielectric environment. Some types of fiber grating such as long period grating (LPG), tilted fiber Bragg grating (TFBG) and etched fiber Bragg grating are also sensitive to the surrounding dielectrical environment (i.e. refractive index), so it has the potentials to be combined with the tunable refractive index property of MF.

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