Inline structure with longitudinal dispersion variation based on a silica micro-structured optical fiber for highly coherent supercontinuum generation

Qi, Wenliang

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**NANYANG
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UNIVERSITY**

**INLINE STRUCTURE WITH LONGITUDINAL DISPERSION
VARIATION BASED ON A SILICA MICRO-STRUCTURED
OPTICAL FIBER FOR HIGHLY COHERENT
SUPERCONTINUUM GENERATION**

QI WENLIANG

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

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**Inline structure with longitudinal dispersion variation based
on a silica micro-structured optical fiber for highly coherent
supercontinuum generation**

Qi Wenliang

School of Electrical & Electronic Engineering

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Abstract

The supercontinuum generation in the pure silica micro-structured optical fibers (MOF), or photonic crystal fiber (PCF) when the cladding air holes are arranged periodically, has been investigated for over more than a decade since its first debut in the year 2000. The mechanism of the supercontinuum generation is mainly affected by the dispersion of the pumping wavelength when short pulse laser is used as a pumping source. The supercontinuum generated by pumping at anomalous dispersion wavelengths usually has a large bandwidth. The drawbacks of this generated spectrum is that the coherence can degrade fast due to influence of modulation instability in the anomalous dispersion region. Thus, it is sensitive to the input shot to shot noises and there can be spectral intensity fluctuation in the generated supercontinuum spectrum. This hinders its uptake in a wide range of applications. On the other hand, pumping at the normal dispersion regime can inhibit the problematic modulation instability. Therefore, highly coherent supercontinuum generation is achievable when pumped at normal dispersion regime. However, usually the bandwidth is limited due to fast peak power dropping by the rapid temporal.

In this work, I develop an inline optical fiber structure with a longitudinal variation based on the silica PCF for the highly coherent supercontinuum generation. In the inline fiber structure, the input pulse is first compressed for a peak power enhancement to overcome the problem of insufficient nonlinear interaction due to the power dropping in normal dispersion region. Then, the spectrum is rapidly broadened in a short length of normal dispersion taper. The normal dispersion taper can inhibit the modulation instability and yield high coherent supercontinuum spectrum. The short length of the small structure taper could reduce the loss from the low confinement in the fiber, as well as the absorption in the silica when the spectrum extends to

above $2\ \mu\text{m}$ region. Besides, the pulse compression and the spectrum broadening occur in one fiber structure, which avoid the additional loss in coupling. The whole inline fiber structure has a short length and could be pumped with commercial picosecond laser for a better performance, which make it compatible with other systems and promising in the real application.

In this thesis, I introduce the background physics including the linear and nonlinear properties of the PCF, theoretical investigation of the supercontinuum generation in the inline fiber structure, fabrication and characterization of the fiber and fiber taper, and finally the experimentally investigation of the pulse compression and supercontinuum generation in the inline fiber structure. The obtained supercontinuum generation is over one octave in bandwidth and extends to above 2158 nm in this silica fiber. The simulation agrees with the experiment result and confirms that the generated spectrum is highly coherent.

Overview of the thesis

In this thesis, I present an inline fiber structure based on silica PCF for coherent supercontinuum generation. This inline optical fiber is originally designed to have three sections with a normal-anomalous-normal dispersion profile. The lengths of each section are determined by the pumping condition. In this inline optical fiber structure, the pulse compression is employed to enhance the peak power for the subsequent coherent supercontinuum generation in the normal dispersion taper. The first normal dispersion section provides with pre-linear-chirp to suppress the undesired side peaks and pedestal for a better compression. The second anomalous dispersion section is the stage where pulse compression occurs to enhance the peak power and shorten the pulse width. Finally, the last normal dispersion section is the main stage that highly coherent supercontinuum spectrum can be obtained. The length of the last section is short, which mitigates the loss either from the low confinement or the absorption in silica where the wavelength extends to above $2\ \mu\text{m}$ region where water related absorption can be serious. The inline structure is designed to be fabricated by a simple tapering process.

I first used the numerical modelling to simulate the pulse evolution in a designed inline optical fiber structure by pumping at 1550 nm. The simulation showed that broad, highly coherent could be generated in this inline fiber structure. The broadened spectrum covered the wavelength above 2 μm region, which was not reported in silica optical fibers. The simulation was also conducted by using only the normal dispersion fiber with the same pumping condition. The comparison showed that the inline fiber structure performed better with five times` the bandwidth in a short fiber.

For the experimental demonstration, I used the two-section inline fiber structure consisting of the section 2 and 3 to illustrate the merits. I fabricated the PCF with the anomalous dispersion using the stack and draw method. Afterwards, the fiber was tapered down with the pitch size and cladding air hole shrunk independently to the desired the structure. The all normal dispersion was achieved around the pumping wavelength of 1550 nm.

The pulse compression was investigated by using a certain length of anomalous dispersion fiber. Input pulses were compressed to about was experimentally compressed to about 60-80 fs (Full width half maximum, FWHM) when the pulse width varied between 600 fs and 200 fs. Subsequently, coherent supercontinuum generation was generated in the normal dispersion taper. Theoretically, the spectral broadening is dominated by the self phase modulation (SPM) of which the modulating feature was seen as the protruding spectral oscillation in the vicinity of pumping wavelengths, together with other uneven components on both neighboring sides due to other nonlinear processes including four-wave-mixing (FWM) and Raman scattering. The spectrum is incompletely developed which is attributed to the low applicable input power limited by the pulse compression. I also used the simulation to model the pulse propagation in the inline structure, and it agreed with the experimental results well. From the simulation, the spectrum was stable with ignorable spectral intensity fluctuation. The calculated spectrogram

and g_{12} quantifying the degree of coherence also showed that the spectrum was generally linear chirped and was highly coherent. The potential optimization of the supercontinuum generation in the inline optical fiber structure was also discussed to achieve more fully developed spectrum. The possible solutions included providing a linear chirp prior to the compression process or shortening the anomalous dispersion section to pump with a higher applicable input power. Besides, a more flat and small dispersion at the pumping wavelength could also greatly favors a better broadening, in spite that it is limited by the present fabrication.

I also modified the dispersion measurement method based on the white light source interferometry to retrieve the dispersion from the phase through simple procedures. Both two background arms are considered to extract the phase to eliminate the potential errors. Combined with removing the influence of the imperfect visibility which brings ambiguousness in the phase retrieval, the method shows good accuracy in the dispersion measurement in optical fibers even the zero dispersion wavelength is excluded in the measurement region.

This work preliminarily demonstrates the feasibility of the coherent supercontinuum generation in the inline optical fiber structure. Further efforts are still required to optimize both in the design and the fabrication process, thus produce compatible broadband white light source for various applications.

The outline of the thesis is as follow:

Chapter 1 first provides the knowledge of the photonics crystal fiber including its excellent features and a brief introduction of the fabrication technique, and the linear properties of the optical fibers, including dispersion, optical loss, etc, which are essential for the supercontinuum generation.

Chapter 2 mainly focuses on the nonlinear interaction in the optical fibers. The effects of the nonlinear factors such as SPM, SPM combined with dispersion, FWM, Raman scattering, modulation instability and so on are introduced. Then, I review of the supercontinuum generation works in optical fibers, especially the coherent supercontinuum generation in the PCFs. Finally, I introduce the numerical modelling to simulate the pulse propagation in the optical fibers.

In Chapter 3, I present the design of the fiber and the inline optical fiber structure. Theoretically, I also investigate the supercontinuum generation with the peak power enhancement in this inline structure.

In Chapter 4, I use two-section inline fiber structure (consisting of section 2 and 3) for the experimental demonstration of supercontinuum generation first. The fabrication and the characterization of the anomalous dispersion section 2 PCF are reported. I also employ a certain length of fiber to experimentally investigate the pulse compression in the fiber.

The fabrication of the normal dispersion taper (section 3) and the supercontinuum generation in the inline structure are finally experimentally demonstrated, as reported in Chapter 5. A broadband supercontinuum spectrum covering above $2\ \mu\text{m}$ region is obtained. I also use the simulation to model the pulse propagation in the inline structure and confirm the coherence.

Last, I give the summary of the work and the future expectation in Chapter 6.

Chapter 1:

Photonic crystal fiber and its linear properties

1.1 Introduction

Photonic crystal fiber (PCF), which is also called the micro structured optical fiber (MOF) when the cladding air holes are arranged periodically, has been proven as an excellent platform for supercontinuum generation due to its unique properties unachievable in conventional solid fibers. In particular, linear properties of optical fibers, such as dispersion, loss and birefringence, have great impacts on the power strength for nonlinear interaction and the mechanisms through which the spectrum is broadened and so on. In this chapter, I mainly introduce fundamentals of fiber optics necessary to understand the supercontinuum generation mechanisms, including PCFs, fiber fabrication, and the linear properties which are the key parameters to control to pursue the coherent supercontinuum generation in the silica PCFs.

I start with a brief introduction of PCFs. The two guiding mechanisms in the PCFs, the modified total internal reflection in solid core PCFs and the photonic bandgap in the hollow core fibers, are briefly presented. The outstanding designing flexibility in the PCFs allows excellent controls over the dispersion, nonlinearity and the loss performance, and the single mode behavior in PCFs, thus customized for various applications, which I also cover in the chapter. Besides, the fabrication of the PCFs with the stack and draw method is described together with the further taper process.

Followed by are the linear properties in optical fiber, including dispersion, loss, and birefringence. Dispersion control is a key to success of the inline structure fiber for a highly coherent supercontinuum generation under short pulse pumping as it determines the mechanism of the nonlinear interaction. The design principle in controlling the dispersion in PCFs is described. Methodologies of dispersion measurement are discussed. I built a setup based on spectral white light interferometric method and proposed an alternative approach to direct phase retrieval method to obtain the dispersion. The modified method shows reliable results even when zero dispersion wavelength (ZDW) is not included in the measurement region. Another key property is the loss, which is usually higher in PCFs than the conventional optical fibers. The high loss can also reduce the power and hinder the supercontinuum generation. Several contributors for the loss in PCFs are discussed below. The loss can be improved by the PCF designs and careful fabrication process. Here, I only focus on the solid core PCF which is desired for a high nonlinear interaction for the supercontinuum generation.

1.2 Photonics crystal fiber

In the past few decades, one of the most important successes in the work on the area of optics is the invention of optical fibers, and their technical advances. The optical fiber technology has been developed very fast and witnessed quite a few remarkable progresses in a wide spectrum of applications from scientific research to industry applications. The most widely received application of the optical fibers is the long haul information transmission at high speed in the telecommunication after the propagation loss was greatly reduced with the progress in the fabrication. Moreover, optical fibers have also already in many other works, such as fiber lasers [1], sensing [2, 3, 4], and some medical systems [5, 6], to name a few, and led to leaps of the technology advances in optics.

Fig.1-1 A typical illustration of a step index optical fiber.

Conventional silica optical fibers consist of high refractive index core and the low refractive index cladding. Fig.1-1 shows a typical step index fiber consisting of the higher refractive index core and lower index cladding. The graded-index fibers refer to the fibers whose refractive index

decreases gradually to the cladding. The light propagates in the core area due to the refractive index contrast caused total internal reflection from the materials. The optical fibers are fabricated using the pure silica glasses, abundantly available in the world. The refractive index difference between the core and cladding could be achieved by doping of other materials. For example, doping the silica glass with germanium oxide can increase the refractive index, making the glass favorable choice for the core, whereas cladding silica is doped with boron or fluorine reducing its refractive index [7]. Regarding to the optical fibers for special applications, some other dopants, such as Er^{3+} for the fiber amplifier, etc, can be incorporated. This kind of fiber is usually fabricated through preform fabrication using deposition methods and subsequent fiber drawing in a furnace at high temperature. The process is quite complicated and the uniformity of the refractive index as well as the constant diameter size should be ensured [8].

Fig. 1-2 An illustration of photonic crystal [9].

Different from the conventional optical fibers, MOFs are optical fibers with micro structures, usually the air holes structure, in the transverse section along the optical fiber. MOFs could also be referred as PCFs when the air holes are periodically arranged. In the rest of the thesis, PCFs also refer to the MOFs. The idea of the PCFs was inspired from the photonic band gap which was widely studied in 80s-90s [10]. Fig.1-2 illustrates some simple examples of 1-D, 2-D and 3-D photonic crystals. The photonic band gap can block the transmission in certain wavelength

ranges and allowing the transmission in the rest through the creation of the right structures. This encouraged the great idea to trap the light inside the optical fibers by a hollow core structure in the center [11]. The band gap in the fiber could be created by a two dimensional photonic crystal in the cladding. Until a few years later, the fabrication of the first PCF was reported [12, 13], as seen by Fig. 1-3 (a). However, this reported PCF did not have a hollow core as the expectation because the fabrication process limited to create a large hollow area in the core. In this PCF with a solid core, the photonic band gap is not the mechanism for confining the light in the fiber. The light is conducted by a modified internal total reflection through the index contrast built by the air holes in the cladding. The benefits of this PCF include the endless single mode guidance and low intrinsic loss since no dopants exists in the core, along with the modifiable dispersion and nonlinearity, to name a few.

The first hollow core PCF was successfully fabricated with a few capillaries removed in the central area [14]. The light was mostly guided within the hollow region while only small portion of light propagated in the silica. The guiding mechanism of this photonic crystal fiber is the photonic band gap. Therefore, the hollow core PCFs are also called photonic bandgap fibers. The hollow core PCF owns a high damage threshold and limited nonlinear interactions since the light is guided in the central air core. Therefore, the hollow core PCFs are not suitable to be directly used for supercontinuum generation usually. However, there still exist the possibilities for the supercontinuum generation in the hollow core PCFs when the fibers are filled with some gases for the nonlinear interactions [15]. Fig. 1-3 gives the images of several PCF designs. In this work, I employed the solid core PCFs for supercontinuum generation.

Fig. 1-3 Photograph of several PCF examples. (a) Solid core PCF [11]. (b) Hollow core PCF [14]. (c) Highly birefringent PCF [16]. (d) Kagome-structured hollow core PCF [17].

1.2.1 Features of solid core PCFs

As is known that two mechanisms dominate the guidance of the light in PCFs, including the index guiding PCFs with a solid core, and the band gap guiding PCFs with a hollow core. The guidance of the index guiding PCFs behaves similarly with the conventional optical fibers. The air holes in the cladding create a refractive index contrast between the cladding and core, thus the light propagates in the fibers through the total internal reflection. This refractive index

difference is created by the air hole structure in the cladding, but not by the dopant materials. Therefore it is also called the modified total internal reflection.

Fig.1-4 A solid core PCF structure defined by the pitch size and cladding air hole diameter.

Fig. 1-4 shows a typical structure of an index guiding PCF. The PCF is defined by the air hole diameter (d) and a hole to hole space, pitch (Λ). The index guiding PCFs own some features different from the conventional optical fibers, one of which is the ability to exhibit the endless single mode behavior that is not observed in the conventional optical fibers. This is explained by the filter modal [18]. The cladding air hole serves as the filter so that higher order modes who have a small lobe dimension could escape more easily from the core area through the "filter".

Increasing the d/Λ (air hole diameter to pitch) ratio can make the filter grid smaller, thus the fiber can trap more high order modes. On the contrary, PCFs with comparable smaller d/Λ ratio can ensure that only the fundamental mode propagates in the core area [19, 20], creating the endless single mode behavior.

The other outstanding feature of the solid core PCFs is the freedom in the design. This opens quite a few opportunities to modify the properties of the PCFs through designing the transverse micro structures in the cladding, such as the air hole diameter, pitch size, the shape of the cladding air holes and the even the number of the air hole layers. These modifications can have impacts on the fiber properties such as dispersion, nonlinearity, the optical loss and the birefringence. The dispersion tailoring is the key in this work, and it mainly relies on the influence of waveguide dispersion through these structures. Thus PCFs can be designed to have different dispersion profiles. Besides, a high nonlinear coefficient could also be expected through reducing the modal area in the small core PCFs. Moreover, the loss and birefringence can also vary by different cladding core contrast and asymmetrical structures. Now the material flexibility can also be incorporated in the design of the PCFs to obtain the PCFs with the doped core or non-silica materials. These PCFs can further extend the transmission window to regions where pure silica fibers could not reach. Besides, the materials usually have higher nonlinear coefficient, therefore result in a higher nonlinear interaction that is favorable for different applications, especially in the supercontinuum generation. The dispersion management can also be achieved in consideration of the material flexibility. Although hollow core PCFs are not used for supercontinuum generation, the air hole areas can provide spaces for various fillers, including both gases [21-24] and liquids [25-27], bringing possibilities for many applications. These air hole spaces could be also filled with the solid materials through deposition so that more interesting phenomenon can be expected. For example, the sensing films or some nanoparticles can be deposited on the inner walls of the air holes for the surface enhanced Raman scattering [2, 28-31], and two dimensional graphite is also participating this process, deposited in the fiber for mode-lock fiber lasers [32, 33] and so on.

1.2.2 Fabrication of PCFs

The most popular fabrication techniques developed for the PCF fabrication include the stack and draw method [13, 34] and extrusion [35, 36]. The stack and draw method, which involves the stacking process, preform drawing and finally the drawing of the PCF, is the most widely used technique for silica PCF fabrication. In this work, I also used this method to draw the PCF designed with anomalous dispersion for pulse compression. The dispersion can be changed by tapering the PCF.

I used two different fiber drawing towers to fabricate PCFs. The fiber drawing tower 1 is used for drawing the capillaries and the canes. This drawing tower consists of a furnace, diameter monitor, clampers and cane puller. The furnace serves as the heating zone, usually performing at the temperature of around 2000 degrees Celsius to soften the glasses. The clamper and cane puller clamp the tubes or preforms and control the feeding and drawing speeds. The diameter of the capillaries and canes are monitored by two sensors. The fiber drawing tower 2 is similar to the tower 1. However, there is no cane puller in tower, and the drawing speed is control by the capstan. Besides, other differences between the two towers include that the fiber drawing tower 2 has the coating dye, UV curer and the collection spool which are used for applying coating and collecting the fiber. A configuration of the fiber drawing tower including both the two towers (differences are marked) is depicted by Fig. 1-5.

The design of the PCF should be completed to fix the pitch size and cladding air hole diameters before drawing the fiber. Thus the size of the capillaries can be estimated. The reason is that the inner/outer diameter of the capillaries largely determines d/Λ ratio [37] in the drawn fiber. Though the d/Λ ratio could be adjusted in later procedures through controlling the drawing

Fig. 1-5 Schematic illustration of the fiber drawing tower system.

conditions such as temperature, pressure, speed, etc. A preferred method is to start with a close structure.

The fiber drawing starts with the stacking of the capillaries. The capillaries are drawn from the commercial available fused silica tubes or rods using the fiber drawing tower 1. To fabricate the PCFs with a solid core structure, high purity F300 glass rod is preferred for the core rod due to a low OH concentration which could lower the water related absorption. The rod is 1 m long and 10 mm in diameter. I used HSQ300 glass tube to draw the cladding capillaries. The tubes are usually 1 meter long. The outer diameter of the tube is 25 mm and the inner diameter is 19 mm. The less pure tube could expand or shrink more so that the cladding air hole size could be more easily controlled by adding pressure. The rod and tubes are drawn downsize to 1 meter long capillaries with the diameter of around 1 mm in diameter, which is determined by the layer number of the cladding air holes and jacket tube diameter. Fabrication of these capillaries is of great importance to the optical fiber collected in the final stage. The uniformity either along one capillary, or among the capillaries, can not only influence the loss in the PCFs, but also have great impact on the uniformity of the structures in the fiber cladding structure. Small difference in this initial stage may be magnified in the final fiber. Therefore, every capillary should be carefully examined before proceeding. The uniformity in diameter and circularity of the capillaries should be controlled to at least 1% in diameter [37].

The capillaries are then stacked by using a stacking machine (designed and made by Mr Dai) to form a hexagonal structure with the solid rod in the central position as the solid core of the fabricated PCF. In the stacking step, a few capillaries can be intentionally removed in the stacked structure to form hollow core PCFs or PCFs with special designs. The capillaries are well stacked and the stack is horizontally inserted into another jacket tube. Some smaller size rods make the inserted stack tighter by replacing some corner capillaries. An illustration of the stack

structure and an end face photograph of an actual stack are shown in Fig.1-6 (a) and (b). All these procedures should be carried out in cleanroom with the assistance of electrostatic ion blower to avoid the contaminant and the electrostatic.

After the stacking of capillaries, the completed stack is drawn to PCF in two stages, namely the preform drawing and the fiber drawing. In the first stage, the stack is first drawn down to the preforms with the length of about 1 meter and 3-4 mm in diameter. The vacuum should be applied to the space among the stacked capillaries during the drawing process. This can remove the air between those capillaries by fusing them. A microscope image of a cane is shown in Fig. 1-6 (c). Before proceeding to the fiber drawing, the air hole size and pitch should be checked in microscope to estimate the feeding and drawing speed ratio in the stage 2.

In the second stage, the preform is inserted into another jacket tube with inner and outer diameters of 5 mm and 10 mm respectively and is then loaded into the furnace. The vacuum is also required between the cane and the jacket tube to remove the between spaces. A pressure in the air holes in the cladding can control the air hole diameter. The pressure can be chosen to be applied which depends on the real PCF structure during the fabrication process. The preform is then drawn to fiber at high temperature in the furnace. A layer of polymer is coated on the silica optical fiber when it passes through the coating die and UV lamp. The purpose is to increase the fiber's strength. Finally, the fabricated fiber could be collected at the collection bobbins. During the drawing process, the temperature, feeding and drawing speeds, and pressure, etc, are all required to be carefully controlled. One fiber sample is shown in Fig. 1-6 (d).

The extrusion method is an alternative choice for fabricating the PCF. A die is needed to mould the molten glass to a certain structure. However, this method is useful for fabricating the PCFs with compound silica glasses, soft glasses and polymers that melt at a lower temperature. A

lack of suitable die materials that withstand a high temperature hinders this process from being applicable for silica PCF fabrication [37].

Fig.1-6 (a) An illustration of a typical stack. (b) The end face image of a stacked capillaries. (c) A microscope image of a cane (d) A SEM image of a fabricated PCF samples.

1.3 Propagation constant

In optical fibers, every discrete modes of the propagating light travels at its propagation constant. The definition of the propagation constant is given by the ratio of complex amplitude of the light

field at the source and at a certain distance, $A(z) = A(0)\exp(\gamma z)$, where γ is the propagation constant expressed as $\gamma = \alpha + \beta i$. Actually, the propagation constant is a complex number with the real part, α , donating the loss or gain in the media and imaginary part, β , which is the product of the effective refractive index and the wavenumber and related to the velocity of the light. Usually, the imaginary part phase constant β is used to refer to the propagation constant. The propagation constant is a frequency dependent feature in optical fiber which determines linear properties of the chromatic dispersion, etc.

1.4 Dispersion

There are a few types of dispersion in optical fibers, including the chromatic dispersion, intermodal dispersion and polarization mode dispersion. Here I refer to the chromatic dispersion when using the term “dispersion” in this thesis. The chromatic dispersion is the dependence of a phase velocity and a group velocity on a light frequency in a transparent medium, and is one of the fundamental characteristics of optical fibers. The property comes from the refractive index variation against the frequency in the transmission window of the fiber.

The frequency dependent feature in the optical fibers can influence the light propagation in various aspects. For example, the short pulses could be broadened due to the dispersion, which brings down the peak power of the pulse or limits the bandwidth in the optical fiber communication system. Dispersion also plays a key role in fiber nonlinearity, such that the formation of soliton in negative dispersion when combined with Kerr effect, nonlinear frequency conversion, to name a few. Thus, dispersion can greatly influence the performance in an optical fiber based systems.

Mathematically, the dispersion could be expressed through the Taylor expansion of the propagation constant $\beta(\omega)$ as a function of the angular frequency ω around a center angular frequency, ω_0 , by:

$$\beta(\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + \sum_{i=1} \frac{1}{i!} \frac{\partial^i \beta}{\partial \omega^i} (\omega - \omega_0)^i \quad (1.1)$$

It also describes the phase shift. The first order term related to the group velocity and describes the overall time delay:

$$\beta_1 = \frac{\partial \beta}{\partial \omega} = \frac{1}{v_g} = \frac{n_g}{c} \quad (1.2)$$

V_g is the group velocity and n_g describes the group refractive index. Physically, the optical pulses propagate with the velocity V_g .

The second order term describe the dispersion, or the group velocity dispersion (GVD), by:

$$\beta_2 = \frac{\partial^2 \beta}{\partial \omega^2} \quad (1.3)$$

This item causes the broadening of an optical pulse. In convention, the dispersion can be also characterized by using the dispersion parameter, D :

$$D = \frac{\partial \beta_1}{\partial \lambda} = -\frac{2\pi c}{\lambda^2} \beta_2 = -\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2} \quad (1.4)$$

When β_2 is positive (or D is negative), the dispersion is usually called the normal dispersion. In the normal dispersion regime, the group velocity for higher frequencies is slower than that for lower frequencies. Similarly, anomalous dispersion refers to the negative β_2 or the positive D . In the anomalous dispersion, light behaves in an opposite way in the fibers that the higher frequency components travel faster.

1.3.1 Dispersion tailoring in PCFs

The dispersion of the optical fiber could be modified because of the impacts from material and waveguide on the dispersion. This dispersion modification has already emerged in the conventional optical fiber that the zero dispersion wavelengths could be shifted through changing the core size or the doping of the material [38]. The emergence of the PCF gives more freedom in dispersion tailor, especially through the designing of the transversal geometry. Thus, in PCFs, the waveguide dispersion may have great impact on the total dispersion. There has been quite a few works on the dispersion tailoring in PCF to achieve ZDW shift [39], all normal dispersion or flattened dispersion [40], and even fiber with multi ZDWs [41].

Waveguide dispersion is attributed by light frequency dependence of waves' phase velocity due to the waveguide. For the fundamental mode in a PCF, this relates to the core size and the confinement of the light. For the single mode PCF, the longer wavelength components of the fundamental mode will spread into the cladding air area, thus less confined in the core area. As a result, the refractive index in the longer wavelength side is closer to the cladding air refractive index, which is usually smaller than that in the core. This could lead to a faster propagation speed. On the contrary, the short wavelength components will be mostly confined in the core area, thus the refractive index of the fundamental mode is close to the core refractive index, and the propagation speed will be slow.

In PCF, the waveguide dispersion is commonly engineered by changing the air hole diameter and the pitch size. I use a simulation to illustrate the influence of d/Λ , pitch size and number of air hole layer on dispersion, shown by Fig.1-7. The influence of the air hole diameter can be inferred by the trend in Fig.1-7 (a) and (b). The d/Λ ratio is effective in modifying the dispersion in a wide wavelength region. It is also noted that the longer wavelength components are more

Fig.1-7 (a) Influence of d/Λ ratio on dispersion when Λ is 2 μm and d/Λ ratio is 0.3, 0.4, 0.5, 0.6, and 0.7. (b) Influence of Λ on dispersion when d/Λ ratio is 0.4, and Λ is 2 μm , 2.5 μm , 3 μm . (c) Influence of the air hole layer on the dispersion when Λ is 2 μm , d/Λ is 0.3, with 5, 6, 8, and 10 layers of air holes in the cladding respectively.

sensitive to this change. When the d/Λ ratio is low, the mode spreads more to the cladding, thus the total dispersion behaves more different from the material dispersion. Whereas, with a higher d/Λ ratio, the dispersion of the fiber is closer to the material dispersion of silica since more light is confined in the core silica area. Similar to Fig. 1-7 (a), dispersion in the longer wavelength side is more modified with the variation of pitch size, as is shown in Fig.1-7 (b). For large pitch size, the core is comparable or larger than most of the longer wavelength components, thus the mode can be well confined in the core area. As a result, the total dispersion is more similar to the material dispersion. For a small pitch size, the dispersion property behaves differently. Besides, the cladding air hole layer number can also influence the dispersion of the PCF, as is depicted by Fig.1-7 (c). The dispersion is more sensitive to the variation at small layer numbers and in longer wavelengths since the light confinement can vary in a significant amount under such circumstances. Thus, when the number of layers increases, the waveguide dispersion becomes less dominant since much of the light is well confined in the core. For example, the dispersion difference between 8 layers and 10 layers of air hole PCF is smaller compared that between the 6 layers and 8 layers cladding air hole PCF, as is seen in Fig.1-7.

1.3.2 Dispersion Measurement

For the dispersion characterization of long length optical fibers, the time of flight technique and the modulation phase shift technique are two widely used methods [42]. The time of flight technique method measure the dispersion through comparing the relative time delay versus wavelength between the tested fiber and the short reference with selected pulses at different wavelengths [42, 43]. On the other hand, the modulation phase shift technique compares the modal group delay dependent phase shifts between modulated input and output signals as a

function of wavelength. [42, 44]. Both methods require long length of optical fibers, typically beyond hundreds of meters or kilometers.

Alternatively, the dispersion can be obtained by the interferometric method. A phase delay caused by an optical fiber relative to the reference, usually the air, induces interference that is useful to retrieve the dispersion. A white-light interferometry uses a broadband light source in a Michelson [45-47] or Mach-Zehnder interferometer [48-51] and it offers precise measurement of thickness, a group refractive index or dispersion for glasses, crystals, and quantum well materials [52, 53]. The white-light interferometry also works well to characterize optical fibers [45, 46, 48-51, 54-56], allowing fiber dispersion measurement with a short length of fiber. Fiber dispersion can be determined using either the temporal or spectral method in this interferometry. The temporal method extracts the group delay from the shift of the cross-correlation interferogram with the varied central wavelength [54]. However, it is vulnerable to external noises associated with the scanning arm [50]. On the contrary, the spectral method counts on the relation between frequency dependent phase of spatial cross-correlation and dispersion. Refractive index obtained by using five-term Sellmeier equation to fit the spectral interference poles was employed to calculate the fiber dispersion [47, 51], but the result is only reliable near the ZWD. Dispersion obtained from relative phase shows high reliability regardless of the locations of ZWDs [50]. A few techniques were employed for the phase retrieval, such as the Fourier transform method [50, 57], the wavelet-transform [46, 58] and direct phase retrieval. The direct phase retrieval can offer simple measurement procedures, but the accuracy is influenced by a precise phase extraction when the interference visibility is low or background spectra from the interferometer arms suffer distortion or fluctuation.

I propose an alternative way to measure the dispersion in optical fibers with interferometric method using direct phase retrieval. The configuration is based on the Mach-Zehnder

interferometer in combination with a broadband supercontinuum source. This measurement refines an interference pattern by correlating two background spectra and the resultant interference, which can avoid potential errors in extracting the phase. The method is verified by measuring a commercial SMF and a PCF fabricated in-house. The measurement shows excellent accuracy and can be applied even in the existence of imperfect visibility and regardless of location of the ZDWs.

Fig. 1-8 The configuration of dispersion measurement based on a Mach-Zehnder Interferometer. S: White light source. L1 -L6: Lenses. M1 -M4: Silver mirrors. BS1 and BS2: 50:50 beam splitters. TS: Translation stage. OSA: Optical spectrum analyzer. FUT: Fiber under test.

Fig.1-8 illustrates the experimental configuration. A supercontinuum source is used as the broadband white light source. The typical output power of the supercontinuum source is between -20 dBm and -30 dBm in our measurement. The beam is collimated by a lens (L_1) and splits into two arms by a 50:50 beamsplitter (BS_1). In the fiber arm, the beam is launched into the fiber under test (FUT) through L_2 . The FUT is typically below 0.5m. The beam exits from the FUT is collimated again by lens L_3 and directed by a mirror (M_4) to another beam splitter (BS_2) which is identical to BS_1 . The other arm serves as a reference arm. A beam in the reference

arm passes through multiple mirrors. The translation stage adjusts optical path difference (OPD) to help to construct a clear interference spectrum. After the silver mirrors, the beam is directed to BS₂ through L₅ and L₆. The two beams are combined at BS₂ and the combined beam is delivered to an optical spectrum analyzer (OSA) through a single mode fiber. The system is also applicable to polarization maintaining fibers by introducing polarizers. The setup is isolated from the air fluctuation or vibration to eliminate undesired external disturbances [59].

An interferogram involves wavelength dependent intensities from a reference arm, $I(\lambda)$, and a testing arm with fiber under test, $a(\lambda)I(\lambda)$, where $a(\lambda)$ describes the relative background in fiber arm to the reference. The measured interference spectrum $I_{int}(\lambda)$ can be generally defined by [55]:

$$I_{int}(\lambda) = I(\lambda) \left(1 + a(\lambda) + 2\sqrt{a(\lambda)}V(\lambda) \cos\left(\frac{2\pi}{\lambda}\Delta d\right) \right) \quad (1.5)$$

where $V(\lambda)$ describes the visibility and Δd represents the OPD between the two arms described by $\Delta d = |L_{air} - n(\lambda)L_{fib}|$. The effective refractive index, $n(\lambda)$, of the optical fiber in a length L_{fib} contains material dispersion, waveguide dispersion and a cross term which describes the effect of the both [55].

Here, I introduce $VS(\lambda)$, from which the interference phase can be extracted, to describe the cosine phase item, $\cos(\frac{2\pi}{\lambda}\Delta d)$, with the influence of the visibility, following the conventional wave representation. $VS(\lambda)$ is given by:

$$VS(\lambda) = V(\lambda) \cos\left(\frac{2\pi}{\lambda}\Delta d\right) \quad (1.6)$$

(a)

(b)

Fig. 1-9 (a): An interference spectrum (red curve in sub-plot (A)) constructed by two background spectra (sub-plot (B)), visibility (sub-plot (C)) and an assumed phase (sub-plot (D)). (b): Potential errors involved in phase retrieval from an interference spectrum. Black dash curve: the cosine phase item from sub-plot (D) in (a). Red solid curve: $VS(\lambda)$, obtained according to Equation (3). Blue solid curve: normalized spectrum with a reference arm. Green solid curve: interference spectrum of sub-plot (A) in (a). The triangle and square markers represent the local maxima and minima.

Maxima and minima wavelengths in an interference pattern determine phase difference, thus phase retrieval. The maxima and minima can be directly identified from the interferogram according to Equation (1.5), and used for obtaining fiber dispersion [51]. The interferogram can be influenced by both the background spectra of both arms and the visibility, hence leading to some errors in locating these interference maxima and minima. Spectrum of the light source was employed to optimize the interferogram [51, 60], however, the errors can still exist.

The possible errors involved in determining the maxima and the minima from the interference pattern are illustrated in Fig.1-9. I postulate irregular power oscillation in the background spectra. The assumed phase and visibility are depicted together with the background spectra by sub-plot (B), (C), and (D) in Fig.1-9 (a). The resultant interference constructed is presented in sub-plot (A) in Fig.1-9 (a). The green curve in Fig.1-9 (b) is directly transferred from the interference pattern (sub-plot (C) in Fig.1-9 (a)). As clearly seen, a maximum wavelength and a minimum wavelength are deviated from the actual cosine phase curve (black) due to the power fluctuation in the background spectrum. A normalization technique using a reference arm spectrum to reduce the deviation is presented as the blue curve in Fig.1-9 (b). However, the normalization is not very effective to eliminate the errors.

To mitigate the potential errors in the measurement, I recalculate $VS(\lambda)$ using both background spectra intensities, $a(\lambda)I(\lambda)$, where $I(\lambda)$, as:

$$VC(\lambda) = \frac{I_{int}(\lambda) - I(\lambda) - I(\lambda)\alpha(\lambda)}{2I(\lambda)\sqrt{\alpha(\lambda)}} \quad (1.7)$$

Using this equation, the recalculated $VS(\lambda)$ is shown in Fig.1-9 (b) as the red curve. The difference between $VS(\lambda)$ and the cosine phase item is attributed to the assumed visibility. Apparently, this recalculated $VS(\lambda)$ represents well the original phase item, hence improves the measurement accuracy.

The visibility in the influenced spectrum is then corrected by employing envelope optimization [61]:

$$\cos\left(\frac{2\pi}{\lambda}\Delta d\right) = \frac{2VC(\lambda) - VC_{up}(\lambda) - VC_{down}(\lambda)}{VC_{up}(\lambda) - VC_{down}(\lambda)} \quad (1.8)$$

where $VS_{up}(\lambda)$ and $VS_{down}(\lambda)$ are fitted upside and downside envelopes of $VS(\lambda)$.

Therefore, the group delay $GD(\lambda)$ and group velocity dispersion parameter $\beta_2(\lambda)$ and $D(\lambda)$

can be simply obtained from the phase $\varphi(\lambda) = \frac{2\pi}{\lambda}\Delta d$ by:

$$GD(\lambda) = \frac{-\lambda^2}{2\pi c} \frac{\partial \varphi(\lambda)}{\partial \lambda} \quad (1.9)$$

$$\beta_2(\lambda) = \frac{-\lambda}{c} \frac{\partial^2 n(\lambda)}{\partial \lambda^2} \quad (1.10)$$

$$D(\lambda) = -\frac{2\pi c}{\lambda^2} \beta_2(\lambda) \quad (1.11)$$

where $\varphi(\lambda) = \frac{L_{air}}{L_{fib}} \pm \frac{\lambda \varphi(\lambda)}{2\pi L_{fib}}$. Its first term, $\frac{L_{air}}{L_{fib}}$, does not contribute to the dispersion calculation

and it vanishes in differential operation.

This method can be applied in various dispersion measurement regardless of the location of the ZDWs and has been verified by the measurement of different commercial fibers and the PCFs fabricated in-house. In this work, I use this method to characterize the dispersion of our fiber samples.

1.5 Optical loss

Optical loss is one of the most important properties in the optical fiber. The loss can be contributed by the intrinsic Rayleigh scattering, imperfection loss, the scattering or absorption

by the impurities like OH [62] and infrared absorption loss. The insufficient confinement of signal modes also leads to loss due to the leakage. This loss is called the confinement loss.

Intrinsically, the losses in silica PCFs are dominated by the water related absorption loss and the imperfection loss [63]. For example, the absorption band in bulk wet (F100) and dry (F300) synthetic silica was measured in [64]. The wet synthetic silica owns a higher attenuation behavior and more absorption peaks compared with the dry synthetic silica as a result of higher OH concentration. For wet silica, the water related absorption becomes even non-ignorable at the wavelengths shorter than 2 μm . This can greatly hinder the fiber's performance in works such as supercontinuum generation in this region. The OH impurities can even penetrate to the core area of the PCF during the fabrication. Therefore, reducing the influence of the water related absorption is quite important and challenging. Usually, a dehydration is introduced in the fabrication which is favorable to reduce the OH concentration [63].

Another factor that contributes to the loss in PCF comes from surface roughness of the air holes. This is called imperfection loss. The surface roughness is possibly brought in during the fabrication process. For example, any scratches on the tubes, the contamination caused by human body and gases in the furnace, can all contribute to this imperfection loss. Besides, diameter fluctuation along the fiber might exist either in the capillary drawing or the fibers drawing process. This can lead to small variation in the cladding air hole diameter and pitch size change along the fiber [63], or making the air holes not identical, which increase the imperfection loss. Therefore, standard operation in the fabrication process is demanded to improve the loss performance.

The insufficient confinement of the guided modes in PCFs can also contribute to the optical loss, which is also the confinement loss. The confinement loss can be obtained by [65]:

$$Loss = \frac{20}{\ln(10)} \frac{2\pi}{\lambda} Im(n_{eff}) \quad (1.12)$$

where $Im(n_{eff})$ is the imaginary part of n_{eff} .

Fig.1-10 depicts the influence of d/Λ ratio, pitch size and air hole layer number on the confinement loss in PCF. As seen in Fig.1-10 (a), the confinement loss become significant across the whole region when the d/Λ ratio is low. The loss in the longer wavelengths is usually higher since the modes spread more to the cladding. While when the d/Λ ratio increases, the confinement loss can be reduced since less energy escapes. Similarly, fiber with the larger core size when the d/Λ ratio is fixed usually has a low confinement loss, as shown in Fig.1-10 (b). However, these can also influence other PCF characteristics such as the endless single mode behavior, dispersion or nonlinear coefficient, etc. Usually, the compromise among them should be considered toward the applications.

The confinement loss can also be reduced by increasing the air hole layer [66], which is probably caused by a tighter confinement of the light in the core due to a higher index contrast with more air holes in the cladding. Fig.1-10 (c) shows the influence of the air hole layer on the confinement loss. With more air holes in the cladding, the confinement loss can be reduced. It is also noted that the dispersion is less sensitive to the cladding air hole layer as discussed. Thus, controlling the air hole layers is a good way to improve the confinement loss in PCFs without compromising dispersion.

Fig.1-10 (a) Influence of d/Λ ratio on confinement loss when Λ is 2 μm and d/Λ ratio is 0.3, 0.4, and 0.5. (b) Influence of Λ on dispersion when d/Λ ratio is 0.4, and Λ is 2 μm, 2.5 μm, 3 μm. (c) Influence of the air hole layer on the dispersion. when Λ is 2 μm, d/Λ is 0.3, with 6 layers, 8 layers and 10 layers of air holes in the cladding respectively.

When the optical fiber is bent exceeding a certain radius, the additional bending loss can also lead to the leakage of the modes. The bending loss increases with longer wavelengths in the solid PCFs [18]. However, even in the short wavelength range, the fundamental mode may also be coupled into the higher order mode due to the bending, and can increase the bending loss by escaping through spaces between the air holes when the wavelength is far smaller than the pitch size.

1.6 Birefringence

The birefringence refers to the linear birefringence which is not power dependent feature. A single mode actually consists of two orthogonal polarized modes. These two orthogonal polarized modes are not coupled and can have different propagation constant. The circular symmetry may be resulted from the purposeful design of the PCFs as is seen from Fig.1-3 (c), or some purposeful the unintentional errors in the fabrication process, along with other factors such as the bending, and impurities and so on.

This linear birefringence is usually characterized by the refractive index different of the two orthogonal polarized modes by:

$$B = |n_x - n_y| \quad (1.13)$$

where n_x and n_y are refractive indexes of the two orthogonal polarized modes.

For a short pulse system, the birefringence can cause spread of the pulse which is also known as the polarization mode dispersion. This could influence supercontinuum generation in PCFs.

1.7 Chapter summary

In this chapter, I first introduced the PCF which is the platform of this supercontinuum generation, including the features and fabrication of the PCF. Then, the linear properties of the PCF, including the dispersion, loss and birefringence are presented. These can greatly influence the supercontinuum in mechanism and the nonlinear interaction strength. In addition, a modified dispersion measurement method was proposed to retrieve the dispersion directly from the phase of interferogram. The results can be reliable regardless of the ZDWs.

Chapter 2:

Nonlinearities in optical fibers and review of supercontinuum generation

2.1 Introduction

In optical fibers, the total intensity of polarization can be expressed by the applied electrical field. This relation contains a linear item and nonlinear items non-ignorable when the intensity of the pumping is high. In Chap. 1, I reviewed a linear response through the refractive index related first order susceptibility, including the dispersion, loss, and birefringence. In this chapter, the main content is the nonlinear interaction in the fiber, which leads to the generation of the new frequencies. The supercontinuum generation is the process of generating new frequency components from the pumping frequency.

In Chapter 2, I first introduce the nonlinear processes that participate in the nonlinear interaction. The nonlinear processes include the nonlinear refraction, the inelastic scattering and some

combined effects by both the linear and nonlinear factors. Among them, SPM, FWM, and Raman scattering dominates the coherent supercontinuum generation by short pulse pumping in normal dispersion region. In contrast, the soliton dynamics by SPM and anomalous dispersion account for the low coherent supercontinuum generation in anomalous dispersion region under short pulse pumping. Modulation instability contributes to the degradation of the coherence in this nonlinear process.

Then, the progress on the supercontinuum generation with optical fibers, especially PCFs, is reviewed. These works include both the supercontinuum generation dominated by soliton dynamics and coherent supercontinuum generation by short pulse pumping, both silica optical fibers and some non-pure silica fibers, the discussion of the mechanisms of the spectral broadening, the influence of the noises and some recently development in this work.

Finally, I briefly introduce the numerical modeling of the pulse evolution in optical fiber by solving the generalized nonlinear Schrodinger equation (GNLSE), which I used for our simulation of the pulse propagation in the optical fibers. I also include the random noises in the numerical modeling to investigate the degradation of coherence and influence of the noises on the spectrum. Besides, the calculation of the spectrogram is included to give a clear view of the generated spectrum.

2.2 Nonlinearity

The medium's response to the high intensity light in the optical fibers can be described by a nonlinear relationship. The response of the total intensity of polarization, P , to the applied electrical field, E , in the optical fibers is given by:

$$P = \varepsilon_0(x^{(1)} E + x^{(2)} E E + x^{(3)} E E E + \dots) \quad (2.1)$$

where ε_0 is the vacuum dielectric constant, $x^{(k)}$ is the k_{th} order susceptibility. In the first term, $x^{(1)}$ is the linear susceptibility, which relates to the linear properties such as refractive index, thus the loss and dispersion, etc. In silica optical fibers, the second order susceptibility is usually 0, thus the second order nonlinear phenomenon is not often observed. The nonlinear effects discussed in this chapter originate from the third order susceptibility $x^{(3)}$ both for elastic and inelastic nonlinearities.

2.2.1 Optical Kerr effect

The optical Kerr effect in the optical fibers describes the instantaneous nonlinear response on the refractive index when a strong applied electrical field is applied. The propagation of the light could be further influenced due to this refractive index variation. The optical Kerr effect belongs to the third order nonlinear optical effects and is one of the main nonlinear effects in optical fibers. The physics behind the optical Kerr effect may include molecule reorientation, electrostriction, etc [67, 68]. The refractive index variation is given by:

$$\Delta n = n_2 |E|^2 \quad (2.2)$$

where n_2 is the nonlinear index which relates to the third order susceptibility. Theoretically, this nonlinear refractive index response is not only related to the electrical field at current time and location, but also related to the electrical field in the past time and neighboring position. However, the pulse width is usually longer than the relaxation time of the refractive index and the beam space is larger than characteristic length of the material's optical Kerr effects. This makes the optical Kerr effect regarded as an instantaneous nonlinear process.

The optical Kerr effects can occur not only in the glasses, but also in other media like gases, etc. A few nonlinear processes originate from the optical Kerr effects, such as SPM in which the nonlinear refractive index variation is caused by the beam itself, cross phase modulation (XPM), in which the nonlinear refractive index variation is caused by other beams, FWM and modulation instability, etc. Those nonlinear effects are of great importance in the spectrum broadening process. Usually, the optical Kerr effect could lead to the increment of the refractive index. However, in some circumstance, the saturation and the decreasing of the refractive index may also occur though at extremely high intensity if the negative item contributing to this index change is not ignorable [69].

2.2.2 Self phase modulation (SPM)

The optical Kerr effect can lead to the intensity dependent refractive index variation, thus cause a phase shift. When considering then intensity of the beam itself as the source of the refractive index variation or phase modulation, this is called SPM. The caused nonlinear phase shift could be described by:

$$\phi_{SPM} = n_2 k_0 |E(z, T)|^2 z \quad (2.3)$$

where n_2 is the mentioned nonlinear index. k_0 is given by $k_0 = \frac{2\pi}{\lambda}$. $E(z, T)$ represents the applied electronic field and z is the propagation length. The SPM induced phase shift is the instant effect and concerns with the intensity of the input pulse and nonlinearity in the fiber. For a short pulse pumping, different frequency components have different phase shift according to Equation (2.3) since the pumping pulse has a temporal profile. Some frequency components may travel faster and some may travel more slowly. This could be regarded as the generation of the new instant frequencies. The frequency difference, also the chirp, can be expressed by:

$$\sigma\omega(T) = -\frac{\partial\phi_{NL}}{\partial T} \quad (2.4)$$

From Equation (2.3) and Equation (2.4), it is known that this frequency difference could grow larger along the propagation distance which also depends on the pulse shape. Thus, the pulse could not only have the temporal broadening in the time domain, but also a spectral broadening in the frequency domain due to the new generation frequency components. For a coherent supercontinuum generation, high input power and high nonlinearity interaction are preferred for a broader SPM induced spectrum.

Fig.2-1 (a) Sub-plot A is the normalized amplitude of a Gaussian pulse and subplot B is the corresponding SPM chirp. (b) SPM induced spectral evolution when dispersion is ignored.

A Gaussian pulse is employed to show the SPM induced chirp and spectral evolution in optical fibers as depicted in Fig.2-1. In the leading edge, the chirp is negative that causes the generation of the lower frequency components, whereas the chirp is positive in the trailing edge higher

frequency components are generated. The chirp is approximately the linear in the central part. The point 1 and 2 depicted by the red star marks in subplot (B) in Fig.2-1 have the same chirp, which also indicates the same instant frequency. As the pulse propagates in the fiber, those components can interfere and form the typical SPM featured oscillation in spectrum as is seen in Fig 2-1 (b). With a higher input peak power and shorter pulse width, the induced chirp could be higher and the spectrum will be more broadened. The broadened spectrum is stable and has a generally fixed pulse to pulse phase relation, thus shows a good coherence performance. Supercontinuum generation by SPM is usually highly coherent and high pumping peak power is preferred for the spectral broadening.

2.2.3 Combined effects by SPM and dispersion

Fig 2-2 (a): Normalized combined chirp (red solid curve) of SPM and anomalous dispersion (black dash). (b): Temporal propagation of a fundamental soliton (left) and a higher order soliton (right) with the amplitudes normalized.

The combined nonlinear properties and dispersion in optical fibers can lead to some new phenomenon during the pulse propagation. One of the interesting phenomena is the formation

of the soliton by the anomalous dispersion pumping. This is of great importance in the supercontinuum generation process.

In the anomalous dispersion regime, the dispersion induced linear chirp is positive in leading edge and negative in trailing edge, acting oppositely to the SPM induced chirp, as illustrated by Fig 2-2 (a). The lower frequency components in the leading edge and the higher frequency components in the trailing edge generated by the SPM travel towards the central part in the anomalous dispersion region, thus the pulse is compressed. When the dispersion induced chirp and nonlinear chirp cancel with each other, the soliton forms.

The calculated soliton has the pulse that can be generally described by a sech function as:

$$E(t) = P_0 \text{sech}(t/T_0) \quad (2.5)$$

The order of the soliton is defined by:

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} \quad (2.6)$$

where γ is the nonlinear coefficient, P_0 is the pulse peak power, T_0 is the pulse duration and β_2 is the group velocity dispersion parameter. The dispersion length L_D and nonlinear length L_{NL} are given by:

$$L_D = \frac{T_0^2}{|\beta_2|} \quad (2.7)$$

$$L_{NL} = \frac{1}{|\gamma P_0|} \quad (2.8)$$

Fig.2-2 (b) is used to illustrate the soliton pulse in the optical fibers. When the soliton order N is 1, the soliton is called fundamental soliton that propagates in the fiber without any temporal or spectral profile variation when only considering the effects from SPM and anomalous

dispersion, as the left subfigure in Fig.2-2 (b). However, when the soliton order is larger than 1, it is a higher order soliton. The high order solitons do not maintain the pulse shape when propagating along the fiber, but periodically break up and restored after the certain distance, which is recognized as the soliton period given by:

$$d = \frac{\pi}{2} L_D \quad (2.9)$$

When soliton order N is not an integer, the pulse will evolve into a soliton and the temporal spreading background. The background is also called the dispersive wave. The right subfigure in Fig.2-2 (b) illustrates the temporal pulse evolution of a higher order soliton. It can be clearly seen that the soliton breaks up and restores periodically. Moreover, in the initial stage, the input pulse is temporally compressed to form a soliton pulse, which is also the soliton compression. The soliton dynamics is mechanism for the short pulse supercontinuum generation by the anomalous dispersion pumping. Usually the generated spectrum owns a larger bandwidth. The soliton compression could also be employed to enhance the pulse peak power for a high nonlinear interaction.

The combined effects from SPM and the normal dispersion lead to less complicated phenomenon. Fig.2-3 (a) illustrates the combined chirp of both SPM and normal dispersion. The normal dispersion induces chirp is the linear up chirp. The chirp is negative in leading edge and positive in trailing edge, which is similar with the SPM induced nonlinear chirp. The negative chirp indicates the generation of the lower frequency components in the leading edge that travel faster in normal dispersion region. The positive chirp in the trailing edge causes the generation of high frequencies that travels more slowly. Therefore, the pulse will be temporally broadened and the peak power is brought down. This will further weaken the SPM as the pulse further propagates. A smaller positive dispersion is helpful for the supercontinuum generation

by slowing down the peak power dropping, and help to create the phase matching condition for the nonlinear interaction through FWM.

Fig.2-3 (a) Normalized combined chirp (red solid curve) of SPM and normal dispersion (black dash). (b): The temporal pulse evolution resulted from the combined effects.

2.2.3 Cross-phase modulation (XPM)

When the refractive index variation in the optical Kerr effects is caused by multiple beams, the nonlinear phase shift could also occur and the new frequencies are generated. The process is referred as the XPM. The nonlinear phase shift caused by XPM is given by [7]:

$$\phi_{XPM} = 2n_2k_0|E(z,t)|_{beam2}^2z \quad (2.10)$$

The additional factor 2 is valid if two beams have the same polarization. When two beams are crossly polarized, the factor could be reduced to 2/3.

2.2.4 Self-steepening

The refractive index can be increased more where the intensity is higher since the optical Kerr effect is intensity dependent. Therefore, the group index in peak area of a pulse is usually higher than the rest. The components in this part might propagate more slowly, leading to the shifting of temporal distribution towards the trailing edge. As a result, a tender leading edge and steep trailing edge will be formed. This could lead to both the temporal and spectral asymmetry of the pulse. The asymmetry of the broadened spectrum could be understood by that the high chirp will be induced in the trailing edge and more blue shift frequency components can be generated.

2.2.5 Four wave mixing (FWM)

FWM also originates from the optical Kerr effects. Different from SPM and XPM, FWM is related to the cross items under the influence of several electric fields. This process depends on the relative phases of all the input beams and the effect can accumulate along the fiber if the phase matching condition is satisfied. If two frequency components ω_1 and ω_2 are propagating in the nonlinear medium, the modulation of the refractive index occurs. This will lead to the generation of two new frequencies components given by $\omega_3 = 2\omega_1 - \omega_2$ and $\omega_4 = 2\omega_2 - \omega_1$ when the phase mismatch given by $\Delta k = \beta_1 + \beta_2 - \beta_3 - \beta_4$ is close to 0 [7]. A degenerate FWM may occur when two of the four frequencies coincide. In this case, two photons with same frequency are annihilated to create a signal photon and an idler photon.

The phase mismatch is attributed to the material dispersion, waveguide dispersion and the nonlinear effects in the optical fibers. The nonlinearity induced phase mismatching is positive and the waveguide dispersion induced mismatching can sometimes be omitted in single mode fibers [7]. In order to make the phase mismatching close to 0, the material dispersion induced

phase mismatching is preferred to be negative. Therefore, working in the anomalous dispersion region is one approach to make three contributors cancel with each other. Lowering the input power could also be helpful to the phase matching condition through lower the effects from the nonlinear factors. However, the low input power requirement is not advantageous to generating new frequencies in supercontinuum generation. A third possibility is to work near the ZDWs, where phase mismatching from material dispersion and waveguide dispersion can be reduced.

2.2.6 Modulation instability

In some nonlinear systems, the phenomenon of modulation instability exists due to the interaction between the nonlinearity and dispersion. This modulation starts from the small perturbation, $a(z, T)$, in the amplitude of the input field. The solution of the perturbation evolution is presented in [7] with a continuous wave input when loss is ignored:

$$a(z, T) = a_1 \exp[i(Kz - \Omega T)] + a_2 \exp[-i(Kz - \Omega T)] \quad (2.11)$$

where a_1 and a_2 are constant numbers, K and Ω are the relative wave number and relative frequency to the input of the perturbation that satisfy:

$$K = \pm \frac{1}{2} |\beta_2 \Omega| [\Omega^2 + \frac{4\gamma P_0 \text{sgn}(\beta_2)}{|\beta_2|}]^{1/2} \quad (2.12)$$

From Equation (2.12), in normal dispersion region, K is a real number for all the frequencies which indicates that no amplification in the amplitude exists. Therefore, the input light will still be stable in the existence of the noise. However, in the anomalous dispersion regime, in frequency range $\Omega^2 < \frac{4\gamma P_0 \text{sgn}(\beta_2)}{|\beta_2|}$, K is complex number so that the perturbation can grow exponentially in amplitude at an expense of the pumping energy. This amplification bands occur in both sides of input frequency. This perturbation can possibly be the noises with random power

and phase, thus which is not predictable. One of the representative phenomena is the formation of a series of pulses from the continuous waves. The modulation instability was experimental observed in anomalous dispersion region of the single mode fiber, which agreed with the theory with two side bands [70].

In supercontinuum generation by short pulse pumping in anomalous dispersion region of a fiber, the generated spectrum usually has the spectral intensity fluctuation and the degradation of coherence due to the modulation instability though the effect may also contribute to the spectrum broadening. In order to suppress modulation instability, a more common approach is to pump in normal dispersion regime where modulation instability is inhibited.

2.2.7 Raman scattering

The nonlinear processes discussed so far are all instantaneous with no energy transferring between the medium and the light. The Raman scattering is different from the optical Kerr effect related nonlinearities. It is not an instantaneous process. One photon is converted into another lower energy photon and an optical phonon whose energy is transferred to the vibration of the crystal lattice. Thus, new frequencies in longer wavelength side are generated. The generated new photons with lower energy are called the Stokes photons. An opposite conversion could also occur with a higher energy anti-Stokes photon emitted when a photon interacts with an existing optical phonon in principle though this process is usually quite weak especially at low temperatures.

The Raman scattering process takes place spontaneously. However, a stimulated Raman scattering can take place in the existence of the Stokes photons, either generated by a spontaneous Raman scattering or from the signal light. The Raman scattering rate can be

increased compared to that of spontaneous Raman scattering, leading to a more efficient conversion from pumping to the low frequency Stokes photons.

2.3 Review of supercontinuum generation

Supercontinuum generation involves nonlinear processes of the spectral broadening and the generation of new frequency components. In the supercontinuum generation, the input laser light is launched into a nonlinear media, and a wide band light source is generated due to the nonlinear interaction. The earliest reported on this white light source was in bulk glasses [71]. Ever since then, supercontinuum generation has been widely studied in different media or waveguides, and leads to the applications in various areas.

Optical fibers offer a good platform for the supercontinuum generation due to the excellent capabilities. The first experimental demonstration of the spectral broadening was in a conventional optical fiber [72]. This had inspired many studies on this nonlinear phenomenon in optical fibers, both theoretical studies and experiment demonstrations, to achieve broader white light source. Moreover, the emergence of PCFs, opened a new door for the supercontinuum generation. PCFs can provide with not only a high nonlinear interactions, but also a high degree of freedom in the design, including transversal geometric structures, materials, and even longitudinal variations, to name a few, thus to obtain the desired waveguide for the spectrum broadening.

The supercontinuum generation follows various mechanisms depending on the input pulse width, and the fiber dispersion at the pumping wavelength. With the short pulse pumping at anomalous dispersion regime, the supercontinuum generation is dominated by a soliton

dynamics [73]. Initially, higher order soliton is formed due to the SPM and the anomalous dispersion. This process is also viewed as the compression process. In this stage, a gradual spectrum broadening takes place. Then, the higher order soliton is perturbed and breaks up into several fundamental solitons, which also refers to the soliton fission. Finally, the solitons continue to propagate with the continuous shift to the longer wavelength side due to the Raman effect. In this soliton evolution process, some of the pulse energy may be transferred to the low amplitude nonsolitonic dispersive wave background. An example of the temporal and spectral evolution of supercontinuum generation by short pulse anomalous dispersion pumping is simulated and shown by subplots in Fig.2-4 (a) using the fiber and pumping pulse in [73].

Usually, a broader supercontinuum generation can be achieved by the short pulse anomalous dispersion pumping. However, the generated spectrum is usually unstable and sensitive to the input shot to shot noises, which is related to the modulation instability [74]. The modulation instability plays an important role in this pulse evolution process since a small perturbation can be amplified in amplitude in the anomalous dispersion region. Fig.2-4 (b) illustrates the sensitivity of the generated spectrum to the input noises by 20 pairs of independent generated spectra when considering the random noises. The black curve represents the average spectrum of all these spectra shown by the grey shadows in the plot. It is noted that the spectral intensity fluctuates quite significantly under the influence of the random noises. Modulation instability is also considered as the cause of the degradation of the coherence in the supercontinuum generation [74]. The simulation of coherence modulus, g_{12} , evolution is shown by the right subplot in Fig. 2-4 (a). In the first few centimeters, the coherence degradation is not serious within a narrow bandwidth since SPM takes an important role in this stage. However, it rapidly degrades across the bandwidth afterwards. This roughly corresponds to the position where pulse splitting takes place.

Superior coherence can be expected when the pumping wavelength moves to the normal dispersion regime where the modulation instability process can be suppressed [74]. However it is also suggested that even the anomalous dispersion pumping can reach high coherence when the input pulse duration is shorter than tens of femtoseconds so that SMP may have higher significance over the modulation instability in the spectral broadening process [73, 74]. The reason is interpreted as this: at a certain peak power level, the fission length of the shorter pulse width is shorter. Thus the pulses evolve faster to reach the maximum spectrum and limited the spectral overlap between the input pulses and the modulation instability gain bands. The coherence can be overall improved [73].

The first report for the optical fiber based supercontinuum generation was by simulation assuming a conventional optical fiber. Due to the lack of proper light source, experimentally demonstration was reported a few years later [75]. The emergence of PCFs opened a new door for the supercontinuum generation due to not only the expected high nonlinearity, but also the unique advantages to modify the fiber properties. Usually the hollow core PCFs are not used for the supercontinuum generation because the light is mainly guided in the air core area where the nonlinear interaction is weak. However, exceptions exist when the nonlinear interaction takes places in other fillers of the hollow core area [24]. This inspires the spectral broadening using the hollow core PCFs as the platform [76]. For example, supercontinuum generation extending from ultraviolet to infrared was reported recently using a hollow core kagome PCF filled with hydrogen with femtosecond pumping [77]. The liquids could also be employed as the filler for supercontinuum work besides the gases [27, 78]. The multicore PCF was also fabricated for the supercontinuum generation to achieve octave span spectrum [79].

Fig. 2-4 (a) An example of spectral evolution (left subplot), temporal evolution (middle subplot) and degree of coherence (right subplot) using a femtosecond pulse to pumping a fiber in anomalous dispersion region. (b) One sliced spectrum calculated from 20 pairs of independently generated spectra when considering random input noise. Black curve is the average spectrum and grey shadow depicts all the spectra.

The solid core PCF is more popular for the supercontinuum generation. This index guiding PCF guides the light through the modified total internal reflection and the nonlinear interaction is

enhanced in the solid core area. Besides, solid core PCF also owns favorable properties of the dispersion tailoring and the high nonlinearity due to the reduction of the effective area, leading to new opportunities. Many work aimed to design PCFs with anomalous dispersion at the pumping wavelengths thus to achieve broad supercontinuum generation through the soliton dynamics [80-83]. J. K. Ranka, etc reported one of the earliest work on supercontinuum generation in PCFs [84]. The designed PCF exhibited anomalous dispersion at visible wavelengths for the first time, and they obtained a 1200 nm broad spectrum by pumping with femtosecond pulses. G. Genty, etc, compared the supercontinuum generation with pumping wavelengths at normal and anomalous dispersion region respectively in the designed PCF and discussed two different mechanisms in the spectral broadening process [85]. They achieved broader spectrum, spanning from 400 nm-1400 nm by the anomalous pumping, than that by the normal dispersion pumping whose bandwidth was limited to 500 nm. The dispersion profile with two ZDWs was also fabricated for supercontinuum generation [86, 87]. The pumping was also in the anomalous dispersion region between two ZDWs which indicated the governing effect was still soliton dynamics [86]. The supercontinuum generation might show some different features, and it was claimed that the main nonlinear interaction was through SPM and FWM, rather than soliton fission though pumping the fiber at anomalous dispersion region [86]. Such a fiber was even tapered to change the dispersion from anomalous to normal to investigate the supercontinuum generation [88]. However, the temporal pulse had already broken up before propagating in the normal dispersion tapers. Some other reports included the various PCF designs at different wavelengths in the visible or near infrared wavelengths [89, 90] using femtosecond pumping pulses.

The longitudinal variation in the optical fibers was also introduced to explore the potentials in supercontinuum generation. The longitudinally varying fiber offers dispersion management

along the fiber and enhancing a nonlinear coefficient by reducing the core area. The dispersion-flattened and decreasing fiber [91], fiber tapers [92, 93] or some multi-section fiber scheme were developed to enhance the nonlinear interaction for broad supercontinuum generation. The longitudinal variation could be introduced to both the PCFs and other fibers. For example, single mode fiber taper was fabricated and used to achieve supercontinuum spectrum spanning from 370 to 1545 nm [93]. Different multimode fiber tapers were also fabricated for efficient supercontinuum generation. Later investigations in PCFs included the zero dispersion wavelength decreasing silica PCFs [94], and PCF tapers [95, 96], etc. For example, a 1400 nm broad supercontinuum generation was reported in [94] using the ZDW decreasing fiber pumped by a sub nanosecond pulse at 1064 nm. In the PCF with longitudinal variation, a careful fabrication is quite important since the transversal micro structures could be much influenced by the fluctuation in the fiber diameter.

Material flexibility was also considered to further extend the transmission window and the supercontinuum generation [97, 98]. Those materials exhibit high nonlinearity compared to silica, and also give high freedoms in dispersion management. The non-silica materials or doped materials were involved in PCF designs to push the wavelengths to mid-IR range. Soft glass PCF was used for ultra-broad supercontinuum generation from 350 nm to 2200 nm with femtosecond pumping centered at 1550 nm [35]. The pulse was also compressed to nearly 34 fs to pump a high nonlinear fiber (HNLF), obtaining supercontinuum generation from 850 nm to 2600 nm [99]. Other materials, such as Tellurite, sulfide, etc, were also helpful to push the effort to longer wavelengths [100, 101]. Especially, over 4000 nm bandwidth supercontinuum generation in a tellurite PCF was observed, covering the wavelength from 789 nm to 4870 nm, when 100 fs pulse centered at 1550 nm was used as the pump.

The supercontinuum generation has various applications including precise frequency metrology [102, 103], optical coherence tomography [104, 105], light sources for optical communications [106, 107], and ultrashort pulse generation [108, 109], to name a few. The coherence of the light source, which describes a stable phase relationship between the electronic field at the different locations or times, is of great importance in a few systems. For example, degradation of the coherence of the supercontinuum generation could limit the application in frequency metrology, ultra-shot pulse generations, etc [74]. Therefore, the supercontinuum generation by the anomalous dispersion pumping is not suitable for these applications since usually the coherence degraded fast in the fiber. As is discussed, highly coherent supercontinuum spectrum could be expected if the pulse width is as short as tens of femtosecond even pumped at anomalous dispersion region. However, a more practical and efficient approach is to pump the fiber in the normal dispersion region where the modulation instability is inhibited [74]. The mechanism of the supercontinuum generation involves the nonlinear effects such as SPM, FWM, and Raman scattering, etc. Higher input pulse power would provide with more sufficient nonlinear interaction. It should be noted that the phase matching condition could also be approximately satisfied at normal dispersion regime close to zero dispersion value for the generation of new frequencies through FWM [110, 111].

The coherent supercontinuum generation has been studied before the emergence of PCFs. Consequently, the spectrum is quite limited by the low nonlinearity in conventional fibers. The generated spectra only covered less than 150 nm [112, 113] when pumped at a communication window with picosecond pulses. The nonlinear interaction could be further enhanced by pulse compression in different optical fibers [114, 115]. For example, the pumping pulse was compressed first to enhance the peak power and achieved coherent supercontinuum spectrum of 325 nm bandwidth [114]. The pump wavelength was selected where the dispersion value

was small. Furthermore, tapering a single mode fiber was investigated for coherent supercontinuum generation [116]. This greatly extended the bandwidth, generating the spectrum spanning from 500 nm to 1300 nm. Multimode fiber tapers were also incorporated in the investigation [92]. Besides, a few works studied the coherent supercontinuum generation using other optical fibers including the high nonlinear fibers [111, 117, 118] and some hybrid fibers [119]. One report experimentally demonstrated a broadband supercontinuum generation from 1100 nm – 2100 nm in a high nonlinear fibers, pushing the wavelength above $2\ \mu\text{m}$ [117].

PCFs are also considered as good candidates for coherent supercontinuum generation since the dispersion can be tailored through the geometry design of the transversal micro structures. The efforts have been made to modify the dispersion for a normal dispersion at the pumping wavelength. One challenge for the coherent supercontinuum generation by normal dispersion pumping is the dropping of the peak power due to the fast temporal broadening, which hinders the SPM. The nonlinearity induced nonlinear chirp and normal dispersion induced linear chirp are both negative in leading edge and positive in trailing edge. They work together to accelerate the process of the temporal pulse broadening, bringing down the peak power. Usually small normal dispersion is preferred in the design of the PCFs in this work. Another potential concern is confinement loss. As is discussed, the dispersion tailoring is mainly achieved by balancing between the material dispersion and the influence of the waveguide dispersion. Most normal dispersion PCFs have small structures or low air filling fraction, thus confinement loss is higher. This confinement loss may be severer in the long wavelength side.

A few PCF designs were proposed and employed to theoretically study the supercontinuum generation. The PCFs included the small structure PCFs, suspended core PCFs and some other special designs [120-124]. For example, flat-top dispersion PCFs were theoretically investigated with a small structure at sub micrometer level and suspended core PCFs were employed for the

coherent supercontinuum generation [120, 121, 124]. In [124], the fabrication tolerance was discussed, and larger fabrication error may exist since the structure size is quite small. To suppress the confinement loss for coherent supercontinuum generation, PCFs with ultra-flat small normal dispersion and low confinement loss were proposed [122, 123]. The cladding air hole diameters were different from layer to layer to control the dispersion and optimize the confinement loss performance. However, fabricating such designs were extremely challenges.

The coherent supercontinuum generation were experimentally demonstrated as well in silica PCFs by normal dispersion pumping. The bandwidth of the generated spectrum was limited, covering only tens of nanometers or a few hundred nanometers in some of the reports [125-127]. A few groups achieved coherent supercontinuum by pumping at the normal dispersion side of the ZDWs, spanning from visible wavelengths to near infrared regions [85, 128, 129]. All normal dispersion fiber provided with good solutions for efficient coherent supercontinuum generation [110, 129-134]. The spectrum covered broad wavelength range to extend the bandwidth to even almost 1000 nm [110, 129-131]. The pumping was usually chosen at the wavelength where the small dispersion value occurs. Moreover, it was indicated the possible non-ignorable influence of the loss on the supercontinuum generation due to small structure with low air filling fraction [110]. The pulse compression was also incorporated with the pulse compression first to enhance the peak power [129]. SMF, large mode area (LMA) fiber and highly nonlinear fiber (HNLF) were spliced together to compress the input pulse before the spectral broadening [134]. The loss could be higher if splicing PCF. Other PCFs such as the PCF tapers, suspended core fiber, etc, also had good performance and showed potential in applications [135-137]. However, all the spectra were limited to the wavelength region below 2 μm . The coherent supercontinuum generation by normal dispersion pumping in pure silica PCF faced the difficulty to extend the spectrum to above 2 μm region by experiment demonstration.

Some experimental results of supercontinuum generation by normal dispersion pumping using silica PCFs are summarized in Table.2-1.

The PCFs made of mid-IR transmitting glasses were also sought to enhance the coherent supercontinuum generation and extends the transmission window. These non-silica PCFs or soft glass PCFs could have higher nonlinearity and their dispersion could also be tailored to achieve normal dispersion through PCF designs. Quite a few non-silica and soft glass PCFs were theoretically proposed to extend the coherent supercontinuum generation to infrared wavelengths where supercontinuum generation in silica PCFs usually could not reach. For instance, all solid all normal dispersion soft glass PCFs [138], As_2Se_3 based PCFs [139-142], square-lattice high nonlinear glass PCFs [143] and ZBLAN fibers [144], to name a few, were all proposed to achieve normal dispersion in a broad wavelength region and have an excellent performance in the coherent supercontinuum generation. The coherent supercontinuum generation covered broadband spectrum from 1.2 μm to 15 μm in [139]. Using As_2Se_2 PCFs by normal dispersion pumping, broadband coherent supercontinuum generation spanning from around 2 μm to 10 μm were also observed [140, 141, 145]. Transferring those design to the real fabrication process might still face some challenges especially in the transversal waveguide structure, such as the As_2Se_3 PCF design with different designed cladding air hole diameters in [142], which is similar to the structure in [122]. However, there were still some successful fabrications that encouraged the work [146-148].

Except the theoretically results presented above, experimental demonstrations of the coherent supercontinuum generation in non-silica or soft PCFs were also reported in recent years. A flat normal dispersion PCFs in near infrared region using N-F2 and NC21 glasses were fabricated and coherent supercontinuum generation spectrum spanning from 950 nm to 1850 nm was obtained by launching 1360 nm pulses with the duration of over 100 femtosecond into the fiber.

Similar works further extended the spectrum to a 900-2300 nm range [149-150]. Chalcogenide PCFs were also fabricated for coherent supercontinuum generation. For example, a chalcogenide PCF with all normal dispersion pumped at around 2700 nm generated the supercontinuum spectrum from 2200 to 3300 nm [151]. An AsSe₂-As₂S₅ hybrid PCF was designed for mid infrared supercontinuum generation [152]. By pumping at 3241 nm at the normal dispersion side of ZDW, a broad spectrum covering from 1580 nm to 5140 nm was obtained. All normal dispersion chalcogenide microwires were obtained to achieve octave spanning coherent supercontinuum spectrum from 960 nm to over 2500 nm [153]. Furthermore, some reported works using step-index non-silica fibers are quite impactful, such as a nearly 3.35 μm wide coherent spectrum was achieved by using the step-index indium fluoride fiber [154]. The state of the art result was achieved in an ultra-high NA chalcogenide step-index fiber [155]. By pumping at the normal dispersion side, they generated an ultra-broad spectrum spanning from 1.5 μm to 11.7 μm , which is the broadest spectrum that is obtained by normal dispersion pumping. The spectrum was further extended to cover the wavelengths from 1.4 μm to 13.3 μm by pumping at the anomalous dispersion region.

Table.2-1 List of a few experiment results of supercontinuum generation by pumping at normal dispersion wavelength using silica PCFs.

Ref	Fiber description	Pumping		Supercontinuum spectrum
		Wavelength	Pulse description	
110	All normal dispersion silica PCF 1	1050 nm	50 fs, 1 kHz, 7.9 nJ	BW* 905 nm
	All normal dispersion silica PCF 2	790 nm	50 fs, 0.9 nJ	425-900 nm

125	Dispersion flattened polarization maintaining PCF	1562 nm	2.2 ps, 40GHz, 6.3W	BW 40 nm
126	Dispersion flattened PCF	1561 nm	170 fs, 0.56 nJ	BW 185 nm
127	All normal dispersion silica PCF	1546 nm	1.6 ps, 10 GHz, 2.14W	1495-1595 nm
129 130	All-normal dispersion silica PCF	1075 nm	350-450 fs, 20 MHz, <1W	BW 800 nm
131	All-normal dispersion silica PCF	800 nm	15 fs, 1.7 nJ	530-1100 nm
132	2.6 μm core PCF	790nm (N**)	15 fs, 16 nJ	510-940 nm
134	Suspended core PCF	456 nm (N)	<100 fs, 6.8 nJ	380-590 nm
135	PCF and PCF taper	809 nm	45 fs, 70 MHz, 190 mW	BW 194 nm
168	PCF	780 nm	110 fs, 76 MHz, 700 mW	400-1400 nm
136	All normal dispersion tapered suspended core PCF	625 nm	50 fs, 1.3 nJ	370-895 nm

*N: Normal dispersion side of the ZDW.

**BW: Bandwidth.

2.4 Numerical Modeling

The numerical modeling of the super continuum generation process is elaborated in [7, 73, 74, 156]. The pulse propagation is modeled using the scalar generalized nonlinear Schrodinger equation (GNLSE). Though frequency domain formulation shows the frequency dependent effects such as dispersion and loss more straightforwardly, it is preferred to use the time domain formulation to model the super continuum generation in optical fibers since this not only favors the interpretation of the physics in the process, but also can be extended to the inclusion of the noise in the input which is feasible to model the stability and coherence of the generated spectrum [73].

The time domain envelope of the electric field is defined by $A(z, T)$, whose complex spectral envelope could be obtained through a Fourier transform. The square of the electric field gives the power of the pulse. The time window is changed into a moving frame by $T = \beta_1 z$, Here β_1 donates the first order differential of the propagation constant $\beta(\omega)$ at the center frequency.

The corresponding GNLSE of $A(z, T)$ is expressed as [7]:

$$\begin{aligned} \frac{\partial A(z, T)}{\partial z} + \frac{\alpha}{2} A(z, T) - \sum_{k \geq 2}^M \frac{i^{k+1}}{k!} \beta_k \frac{\partial^k A(z, t)}{\partial T^k} \\ = i \left(\gamma + i\gamma_1 \frac{\partial}{\partial T} \right) \left(A(z, T) \int_0^\infty R(t') |A(z, T - t')|^2 dt' \right) \end{aligned} \quad (2.13)$$

The left side of the above equation models the linear contributors. α is the linear loss and β_k is the k_{th} order dispersion coefficient by expanding the propagation constant $\beta(\omega)$ with the Taylor series expansion expanded at the carrier frequency ω_0 .

The right side of the equation models the nonlinear effects. γ is the nonlinear coefficient given by :

$$\gamma(\omega_0) = \frac{\omega_0 n_2(\omega_0)}{c A_{eff}} \quad (2.14)$$

where n_2 is nonlinear index, regarded as a constant with the value of $2.6 \times 10^{-20} \text{ m}^2/\text{W}$ in fused silica. A_{eff} is the mode effective area given by:

$$A_{eff}(\omega) = \frac{(\iint_{-\infty}^{+\infty} |F(x,y)|^2 dx dy)^2}{\iint_{-\infty}^{+\infty} |F(x,y)|^4 dx dy} \quad (2.15)$$

where $F(x,y)$ is the transversal modal distribution of the fundamental mode in the optical fibers. γ_1 is simply given by $\frac{\gamma_1(\omega_0)}{\gamma(\omega_0)} = \frac{1}{\omega_0}$. This item is associated with the effects including self steepening. $R(t)$ is the nonlinear response function including both the instantaneous electronic and delayed Raman contributions. It is given by:

$$R(t) = (1 - f_R)\sigma(t) + f_R h_R(t) \quad (2.16)$$

f_R represents the delayed Raman contribution with the value of 0.18 in silica. $h_R(t)$ is the Raman response function usually given by:

$$h_R(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp(-\frac{t}{\tau_2}) \sin(\frac{t}{\tau_1}) \quad (2.17)$$

where τ_1 is 12.2 fs and τ_2 is 32 fs in silica.

The time window and grid in the simulation are carefully selected to ensure that the time delay is within the selected time window and obey the Nyquist sampling theorem. The time window can be determined by the trial to observe if the walk-off of the pulses exceed the time window over the full length of fiber. For the second requirement, generally there is a restriction on the temporal grid spacing, Δt :

$$\frac{\lambda_0}{2c} < \Delta t < \frac{1}{2c(\frac{1}{\lambda_s} - \frac{1}{\lambda_0})} \quad (2.18)$$

where λ_0 is the central wavelength, λ_s is the short wavelength limit and c is the light speed. The temporal grid spacing and time window together determine the number of the grid points used. Usually the number of the points is to a power 2 in order for a fast Fourier transform. For example, for the simulation in this work, I chose the time window of 11 ps, and expected the short wavelength limit to be smaller than 850 nm with the central wavelength of 1550 nm. The temporal grid spacing then should be larger than 2.58 fs and smaller than 3.14 fs. Therefore, I use 2^{12} points corresponding to the temporal grid spacing of 2.68 fs in the simulation. The GNLSE is solved using a split-step Fourier method where the linear operator including the loss and dispersion and the rest nonlinear operator can be functioned separately when the pulse propagates a small step in optical fibers [7].

The effects of noises could be modeled through adding the stochastic influence on the input electric field. The noise can be introduced as a random phase or amplitude [73, 74, 157-159]. Here I used the noise model from [159] including the effects from both the amplitude and the phase. The input temporal electrical field is modeled as:

$$A'(0, T) = A(0, T) \left[\exp\left(\frac{i\xi T^2}{2}\right) + \eta \mathcal{N} \exp(i2\pi \mathcal{U}) \right] \quad (2.19)$$

where $\mathcal{N}$ is a normally distributed random variable whose mean value and standard deviation are 0 and 1 respectively. $\mathcal{U}$ is a uniformly distributed random variable between 0 and 1. η is the noise factor indicating the amplitude of the noise relative to the input pulse amplitude. In consideration of the random input noises, it can be noted how the noises influence the amplitude and phase when the pulses propagate in the fiber. Moreover, it gives details of the single cycle pulse evolution, which are not observed in the experiments.

The coherence, which describes the pulse to pulse phase stability, can also be calculated from a multiple simulation. The coherence degradation of the generated spectrum is quantified by the modulus of the complex degree of first order coherence calculated over a finite bandwidth considering the noise influence [73, 74].

$$\left| g_{12}^{(1)}(\lambda, t_1 - t_2) \right| = \left| \frac{\langle E_1^*(\lambda, t_1) E_2(\lambda, t_2) \rangle}{\sqrt{[\langle |E_1(\lambda, t_1)|^2 \rangle \langle |E_2(\lambda, t_2)|^2 \rangle]}} \right| \quad (2.20)$$

The angle brackets denote the ensemble average of the super continuum pairs, depicted by E_1 and E_2 , generated independently with different random noise. The $\left| g_{12}^{(1)}(\lambda) \right|$ is usually calculated at the $t_1 - t_2 = 0$ corresponding to the fringe visibility. The spectral average coherence is useful to quantify the overall coherent performance. It is defined by:

$$\langle |g_{12}^{(1)}| \rangle = \frac{\int |g_{12}^{(1)}(\lambda)| |E(\lambda)|^2 d\lambda}{\int |E(\lambda)|^2 d\lambda} \quad (2.21)$$

The value is positive and lies between 0 and 1, where 1 indicates a perfect coherence and 0 means incoherence.

The spectrogram is utilized to give a more complete characterization of the optical pulse in the intensity and phase. The spectrogram, which is calculated through short time Fourier transform, is given by:

$$s(\omega) = \left| \int_{-\infty}^{\infty} E(t) g(t - \tau) e^{-i\omega t} dt \right|^2 \quad (2.22)$$

where $g(t - \tau)$ is the variable gate with the delay of τ . Through these short time Fourier transforms, the spectrogram correlates the temporal feature of a pulse to the spectral feature, giving a fuller view of the phase properties of the optical field.

The programming procedures are as follow:

- (1) Determine the input parameter. The input parameter including the peak power, duration, input filed shape of the input pulse, dispersions, nonlinear coefficient, loss and length of the fiber. Some other parameters include the time window, grid spacing, etc, which has been discussed in the above content. The noise could be included by add the turbulence descripted by Equation (2.19) to the input field.
- (2) Substitute the input parameter into the function that solves the GNLSE with split-step Fourier method. The theory has been mentioned above. The reference function could be found in both [7] and [73]. In order to comply with the multi-section fiber, the output pulse of the last fiber section is regarded as the input pulse of the next fiber section and substituted into the GNLSE solver function.
- (3) Regarding of the simulation of the coherence, different noise seeds are modelled in the input field as mentioned in 1. The solver function is run 100 or 200 times and the results of each run are all recorded. The coherence could be calculated by Equation (2.20) with the recorded results.
- (4) The output results could be further processed as is required, including spectrogram, etc.

2.5 Chapter summary

In this chapter, I first present the nonlinear processes in the optical fibers which forms the mechanism of the supercontinuum generation. Then, I give a literature review of the supercontinuum generation, including works on both theoretical and experimental investigation, coherent and incoherent superonctinum generation, PCF and other optical fibers, silica optical fibers and soft glass, non-silica optical fibers. The mechanism of the supercontinnum generation

by short pulse pumping is also presented. Finally, I present the numerical modeling methods of the pulse evolution in optical fiber and characterization of the pulse.

Chapter 3:

Inline optical fiber structure design and numerical investigation of supercontinuum generation

3.1 Introduction

High coherence of the supercontinuum generation is required for the applications such as precise frequency metrology [102, 103], ultrashort pulse generation [108, 109], to name a few. Coherent supercontinuum generation is preferred to be obtained by normal dispersion pumping as discussed in the previous chapter. However, it is challenging to meet the requirement in the pure silica PCFs towards long wavelength supercontinuum. First, the normal dispersion could temporally broaden the input pulse, bringing down the peak power of the pulse. This impedes

the effective nonlinear interactions during the pulse propagation. Besides, the nonlinearity in PCF can also accelerate the pulse broadening and power dropping when combined with normal dispersion, as discussed in Chapter 2. Second, the designed all normal dispersion PCFs usually have a small structure, thus the confinement loss in the fiber can be quite significant, especially in the longer wavelength side. This may chop the generated spectrum [110]. Third, in the silica optical fibers, the water-related absorption can influence the spectral broadening in infrared region.

In this chapter, I propose an inline optical fiber structure. The inline structure is based on the silica PCFs and composed of three sections. Each section possesses different dispersion properties to facilitate pump compression, and subsequent SC generation. The inline fiber structure could enhance the input pulse power first to achieve high peak power and short pulse duration, which is favorable for the high nonlinear interaction and improvement in the coherence. I theoretically studies the PCF designs of each section and the influence of fabrication tolerance on the fiber properties including dispersion, confinement loss and effective area of the fundamental mode. I also investigate the pulse compression in the first two sections under different conditions, such as input pulse duration, peak power, fiber dispersions and chirp, etc, to determine the corresponding optimized section length. Finally, I numerically present the coherent supercontinuum generation to demonstrate the merits of the proposed prototype of the inline structure. Previously, a pulse compression was employed to achieve the high peak power with short pulse duration before launching the light into the normal dispersion PCFs [114, 129]. Long optical fibers were used in the configuration. The fiber for compression was different from the optical fiber for supercontinuum generation, thus the two stages were separated, leading to additional loss in coupling. Splicing in PCFs could also induce large loss. Thus, my approach

using inline structure provides technical advances in integrating all the requirements in a short piece of fiber.

3.2 Inline optical fiber structure

As discussed above, the coherent supercontinuum generation by normal dispersion pumping usually owns limited bandwidth due to either the insufficient nonlinear interaction caused by peak power dropping or the influence of the loss in the fiber, etc. One approach is to enhance the peak power of the input pulse before the pulse propagates in the normal dispersion fiber and employ a short length of fiber for the SC generation so that the loss could be greatly reduced. The peak power enhancement can be achieved by the pulse compression process. After the pulse compression, the peak power of the pulse could be enhanced to a high level. In the meantime, the pulse width could also be shortened which is favorable for the improvement of the supercontinuum generation [74].

The pulse compression has been reported in many works. In the reports in [114] and [129], pulse compression and supercontinuum generation were in different optical fibers. Usually the anomalous dispersion fibers with low nonlinearity, including hollow core optical fibers or large mode optical fibers, etc, were employed to compress the pulse in the first stage. The light source may be chirped before the compression. One merit of these optical fibers is that the compressed pulse could have a cleaner pulse shape. The pedestal and the side peaks of the pulse are avoided so that the coherent supercontinuum generation in the subsequent normal dispersion optical fibers could have a flat spectrum and large bandwidth. However, long fiber was needed. For example, 4 km long non-decreasing anomalous dispersion optical fiber was used in [114] and 15 meters long hollow core optical fiber was employed to compress the strongly chirped pulses in [129]. Another issue is that the compressor and the waveguide for coherent supercontinuum

are different type of optical fibers. The compressed pulse is launched again to the normal dispersion fiber so that additional loss could occur in both the coupling processes. Even the splicing of different fibers were also reported to investigate the supercontinuum generation, the loss could also be quite high in the PCFs.

Fig.3-1 Inline optical fiber structure based on silica PCF consisting of 3 sections. The upper right inset illustrate the PCF design. The input pulse is launched into section 1 and section 3 is the output end.

In this work, I propose an inline optical fiber structure based on silica PCF with the longitudinal variation employing both the pulse compression and the subsequent coherent supercontinuum generation. The purpose is to enhance the peak power and reduce the pulse width by a pulse compression process for the nonlinear interaction to generate coherent supercontinuum generation in the final normal dispersion fiber. This inline PCF fiber structure consists of three sections, as is illustrated by Fig.3-1. The designed the pumping wavelength is 1550 nm. The section 1 and section 2 are used to compress the input pulse. The pulse is desired to maintain

one peak without fission after the compression in section 2. Then, the peak power of the input pulse is enhanced to a high level, and at the same time, the coherent property of the subsequent supercontinuum generation could also be improved since the pulse width could be much shortened. The section 2 possesses the anomalous dispersion at the pumping wavelength. In the optical fiber, the down-chirp is provided by the anomalous dispersion while the up-chirp is induced by the SPM. The SPM induced chirp is not nonlinear, but it could be regarded to be linear in the central pulse area. However, the phase shift caused the SPM and the anomalous dispersion could not be ideally cancelled with each other in only the anomalous dispersion fiber, resulting in the pedestal and side lobes of the compressed pulse. A pre-linear chirp could be helpful to suppress the side peaks so that a higher compressed peak power could be achieved [162]. Therefore, section 1 with the normal dispersion is designed to provide the pre-chirp for the compression. The peak power of the compressed pulse could be further enhanced. Then the compressed pulse seamlessly enters the section 3 with the normal dispersion for the coherent supercontinuum generation. The section 3 is the main stage of the spectral broadening. In order to slow down the peak power dropping and strengthen nonlinear interaction through SPM and FWM, etc, the PCF with a small normal dispersion and higher nonlinearity is preferred. Besides, the loss could also be an important factor that influences the supercontinuum generation process. The loss can be possibly caused by the insufficient confinement of the fundamental mode and the water-related absorption in silica [64] if the spectrum is extended to long wavelength side near $2\text{ }\mu\text{m}$ regions. In order to reduce the influence of the loss, a short length of section 3 is preferred. The inline optical fiber structure can be completed by a fiber tapering process. The all fiber inline PCF structure can be helpful to avoid the extra losses caused by the multi couplings if the compression section and spectrum broadening section separate or by the splicing between the PCFs. The structure difference between PCF designs of the respective sections is expected to be small so as to lower the possible loss.

3.3 Designs of section 1 and 2 for pulse compression

The optical fiber is modeled using the Polymode package in Python language [163, 164]. The package provides with the fiber properties including the confinement loss, and effective area, and the effective refractive index, etc.

The programming procedures are as follow:

- (1) Create the waveguide with microstructure using Polymode package. The geometric structure including pitch, cladding air hole diameter, air hole layer and symmetry, and the materials of the fiber (in this work, we only use air and silica) should be set according to the design. The calculation resolution should also be determined. The resolution could be as high as possible.
- (2) Using the solver to calculate the fundamental mode information in a wavelength range with a certain wavelength step. The modal information at different wavelengths could be automatically obtained in a loop. The related information such as effective refractive index, confinement loss, and effective area, etc, should be recorded while calculation is ongoing.
- (3) Fit the fundamental mode effective refractive index with polynomial fitting in Matlab. The dispersion could be calculated according to Equation (1.10) and Equation (1.11) by twice differentiating. The nonlinear coefficient of the fiber is calculated according to Equation (2.14) with the effective area. Confinement loss could be directly plotted with the calculated results.

The manual on the Polymode mode package can also be found at [163].

Table. 3-1 Dispersions of the section 2 fiber.

	Dispersion value		Dispersion value
β_2 (ps ² /km)	-64.47	β_8 (ps ⁸ /km)	3.717×10^{-13}
β_3 (ps ³ /km)	0.184	β_9 (ps ⁹ /km)	-3.593×10^{-15}
β_4 (ps ⁴ /km)	-3.77×10^{-4}	β_{10} (ps ¹⁰ /km)	3.048×10^{-17}
β_5 (ps ⁵ /km)	7.42×10^{-7}	β_{11} (ps ¹¹ /km)	-2.171×10^{-19}
β_6 (ps ⁶ /km)	8.317×10^{-10}	β_{12} (ps ¹² /km)	1.189×10^{-21}
β_7 (ps ⁷ /km)	-3.167×10^{-11}	β_{13} (ps ¹³ /km)	-4.355×10^{-24}

The dispersion of the PCF is of great importance in the design. However, the trade-off between the dispersion, nonlinearity and the loss should be considered. For example, the PCF design with the desired normal dispersion may own the undesired loss or nonlinear properties [110]. Besides, the feasibility in the fabrication of such a fiber is another concern. Some proposed PCF designs, such as the PCF proposed in [122, 123], may have a quite flat normal dispersion and low confinement loss at the pumping wavelength, which indicates that the designs are good candidates for the final section for coherent supercontinuum generation. In addition, introducing a small core hole to the identical cladding holes for the PCF designs might also be favorable to achieve a desired dispersion profile and low loss. However, such design is extremely challenging to fabricate. Here, I consider a best compromise among the requirements. I decided to use the PCF with a solid core and the surrounded identical cladding air holes. In the numerical analysis, I assume that the PCF has 8 layers of air holes in the cladding with hexagonal lattice.

The PCF of the section 2 which possesses the anomalous dispersion at the pumping wavelength region is designed with the pitch size of 3 μm and the cladding air hole diameter of 1.2 μm . The GVD parameter β_2 is -64.47 ps^2/km at 1550 nm. In the numerical modeling of the pulse evolution of supercontinuum generation, usually the dispersions up to 6 or 12 items are employed [7]. I involve the higher order dispersions of 12 items. The values of the higher order dispersions of the PCF from β_2 to β_{13} are listed in the Table.3-1. I also employ the confinement loss at the pumping wavelength as the representative loss of the fiber design. The confinement loss calculated in the simulation is 1.46×10^{-4} dB/km. Thus the main contribution of the loss comes from a material loss which is also very low, 0.2 dB/km in a telecommunication fiber. Consequently, I ignored the loss in simulation. The effective area of the fundamental mode is 8.352 μm^2 and the corresponding nonlinear coefficient calculated by Equation (2.14) is 0.0131 $/(\text{W} \times \text{m})$. In the fabrication process, the parameters can be deviated due to fabrication errors. Therefore, I theoretically investigate the fabrication tolerance of the PCF design with the pitch size and cladding air hole diameter variation of $\pm 5\%$ on the fiber properties including the dispersion, confinement loss and the effective area of the fundamental mode, which is shown by Fig.3-2.

I first investigate the changes in the dispersion profile (Fig. 3-2 (a)), confinement loss (Fig. 3-2 (b)), and effective area (Fig. 3-2 (c)) when only the pitch size in this fiber design varies within a five percentage. This variation has a small influence on the dispersion profile, as seen in the figure. The core size is larger than the wavelength so that the light is not much spread into the cladding area. Therefore, the variation will not obvious change the dispersion of the fiber. The β_2 value at 1550 nm changes from -60.8 ps^2/km to 68.7 ps^2/km which is acceptable. In some other wavelength, the variation is even smaller. The PCF originally has a small confinement loss. The influence of the pitch size in the confinement loss is remaining at a low level so that it

can be ignored. However the change in the effective area should be considerable. The effective area varies from $7.33 \mu\text{m}^2$ to $9.45 \mu\text{m}^2$, with the corresponding nonlinear coefficients of $0.0116 /(\text{W}\times\text{m})$ and $0.0149 /(\text{W}\times\text{m})$ respectively.

Same with the above discussion, if only the cladding air hole diameter changes within a 5 percentage, or both the pitch size and cladding air hole diameter changes, the dispersion of the fiber is not much different, as shown by Fig.3-2 (d) – (i). The confinement loss remains still at the low level that could be ignored. The only non-ignorable factor is the nonlinear coefficient result from the variation of the effective area of the fundamental mode. However, this might be compromised with the section 1 fiber.

Table.3-2 Dispersions of section 1 fiber

	Value		Value
$\beta_2 (\text{ps}^2/\text{km})$	27.42	$\beta_8 (\text{ps}^8/\text{km})$	-5.71×10^{-12}
$\beta_3 (\text{ps}^3/\text{km})$	-0.146	$\beta_9 (\text{ps}^9/\text{km})$	2.665×10^{-15}
$\beta_4 (\text{ps}^4/\text{km})$	5.44×10^{-4}	$\beta_{10} (\text{ps}^{10}/\text{km})$	9.98×10^{-16}
$\beta_5 (\text{ps}^5/\text{km})$	1.14×10^{-6}	$\beta_{11} (\text{ps}^{11}/\text{km})$	-1.923×10^{-17}
$\beta_6 (\text{ps}^6/\text{km})$	-4.64×10^{-8}	$\beta_{12} (\text{ps}^{12}/\text{km})$	1.967×10^{-19}
$\beta_7 (\text{ps}^7/\text{km})$	6.42×10^{-10}	$\beta_{13} (\text{ps}^{13}/\text{km})$	-1.132×10^{-21}

(a)

(d)

(b)

(e)

(c)

(f)

(g)

(h)

(i)

Fig.3-2 Fabrication tolerance of section 2. (a), (b) and (c) depict the influence of $\pm 5\%$ variation of the pitch only on dispersion, confinement loss and effective area respectively. (d), (e) and (f) depict the influence of $\pm 5\%$ variation of the cladding air hole diameter only on dispersion, confinement loss and effective area respectively. (g), (h) and (i) correspond to the influence of $\pm 5\%$ variation of both the cladding air hole diameter and the pitch size on dispersion, confinement loss and effective area respectively.

The PCF design of the section 1 possesses the normal dispersion at the pumping wavelength region. The function of section 1 is to provide with the pre-chirp for a better compression in section 2. Sufficient linear chirp from the dispersion, or even the SPM in the central part of the pulse, may be helpful for the compression [162]. However, some nonlinear phenomenon including wave breaking [165, 166] and Raman effect [167] in section 1 or 2, may not be favorable for the compression if the phase difference between some components could not be well compensated by the anomalous dispersion. This can lead to an unclear compressed pulse. In addition, the high confinement loss in section 1 could also harm this peak power enhancement process. In this inline PCF structure, the section 1 is designed with the pitch size of 2 μm and the cladding air hole diameter of 0.6 μm . The dispersion curve of the fiber is depicted by the red curve in Fig. 3-3 (a). The GVD parameter β_2 is 27.4 ps^2/km at 1550 nm. The values of the higher order dispersions of the PCF from β_2 to β_{13} are listed in the Table.3-2. The representative confinement loss at 1550 nm is 7.28 dB/m. The loss is not negligible and will surely influence the compression. The effective area of the fundamental mode is 6.36 μm^2 and the corresponding nonlinear coefficient is 0.0172 $/(W \times \text{m})$. Although the dispersion might need to be optimized further, the reason to choose this PCF design is that the confinement loss is fair to be accepted if only a few centimeter PCF is used. Thus, the design is a good compromise. Besides, the fiber needs to stay in normal dispersion region even if the structure size fluctuates due to fabrication. I also theoretically investigated the fabrication tolerance of the PCF design with the pitch size and cladding air hole diameter variation of $\pm 5\%$ on the fiber properties shown by the Fig.3-3.

The influence of $\pm 5\%$ variation of the pitch size only on the fiber properties of dispersion, confinement loss and effective area is presented in Fig.3-3 (a), (b) and (c). Due to the small structure of the fiber design, the influence on the dispersion is more obvious compared to the section 2 PCF, especially in the longer wavelength side. The β_2 value at 1550 nm ranges from

19.9 ps²/km to 36.7 ps²/km. The difference could be greater towards the longer wavelength side. Besides, the confinement loss at 1550nm is 5.88 dB/m and 9.27 dB/m when the pitch size is reduced and increased by 5% respectively, which is not negligible. The nonlinear coefficient ranged from 0.0152/(W × m) to 0.0196/(W × m) influenced by the variation in the effective areas.

The fiber also has a low tolerance on the air cladding hole diameter as illustrated in Fig.3-3 (d), (e), and (f). Reducing the air hole size will make the dispersion flatter. However, this also brings a higher confinement loss. The loss will be increased to 21.9 dB/m. The nonlinear coefficient will also decrease to 0.0156/(W × m). Increasing the air hole size turns out to be opposite. If the pitch size and the air cladding hole diameter change together, the dispersion will shift upside or downside as illustrated in Fig.3-3 (g). The loss behavior is similar to the results discussed above. The effective area is less influenced compared to the pitch size variation as discussed above.

The PCF for section 3 has a contradicting requirements of low normal dispersion, low loss and high nonlinear coefficient for the supercontinuum generation. However, fulfillment of these requirements is difficult, especially for real demonstration. For example, more flat small normal dispersion could be achieved by increasing the pitch size of the PCF in section 1 as depicted in Fig.3-3 (a). This can be more favorable to enhance the nonlinear interaction through SPM and FWM for the supercontinuum generation. However, the nonlinear coefficient will be brought down due to a larger effective area and the confinement loss can be severer due to the lower air filling fraction. Finding the best compromise is necessary. The PCF in section 1 owns a small normal dispersion at 1550 nm. Furthermore, decreasing the air filling fraction for smaller dispersion can lead to higher confinement loss. Therefore, in the simulation, I also use the same design of the section 1 as the PCF for section 3 to illustrate the merits of the inline structure.

(a)

(d)

(b)

(e)

(c)

(f)

(g)

(h)

(i)

Figure 3-3 Fabrication tolerance of section 1. (a), (b) and (c) depict the influence of $\pm 5\%$ variation of the pitch only on dispersion, confinement loss and effective area respectively. (d), (e) and (f) depict the influence of $\pm 5\%$ variation of the cladding air hole diameter only on dispersion, confinement loss and effective area respectively. (g), (h) and (i) correspond to the influence of $\pm 5\%$ variation of both the cladding air hole diameter and the pitch size on dispersion, confinement loss and effective area respectively.

3.4 Determination of the section lengths

The section lengths should also be carefully determined, especially the lengths of the section 1 and section 2 to achieve a good performance in pulse compression. I use the numerical modeling described in Chapter 2 to investigate the pulse compression in the first two sections, thus determine the section lengths with a certain input pulse. With a certain input pulse, I scan the section 1 length with the step of 1 mm. The way is like this: with every fixed length of section 1, the length of section 2 is optimized by monitoring the peak power enhancement. I compare these peak power enhancement factors by increasing section 1 lengths by 1 mm and choose the structure with the highest enhancement.

The ultrashort pulse from the mode-locked lasers usually has a temporal shape (power versus time) that could be described with the squared hyperbolic secant (sech) function. Therefore, I also use the secant pulse as the input pulse in the numerical modeling. The pulse is described as:

$$E(t) = \sqrt{P_0} \operatorname{sech}(t/T_0) \quad (3.1)$$

where P_0 is the peak power of the input pulse. T_0 is the half width defined at $\frac{1}{e}$ intensity point. The full width at half-maximum pulse width is approximately 1.76 times T_0 . Here I use the enhancement factor to characterize the compression performance as:

$$EF = \frac{P_c}{P_0} \quad (3.2)$$

where P_c is the peak power of the compressed pulse. The enhancement factor here differs from the compression ratio which characterize the pulse with pulse width ratio. Usually, the enhancement factor is smaller than the compression ratio due to the pedestal or the side peaks which can store some energy. The simulation is conducted by taking the output of section 1 as

the input of section 2. Considering the worst situation, I also introduce the certain loss in the transition part between the sections.

3.4.1 Compression with different pulse width

For a better pulse compression, the bandwidth of the input pulse should be increased by SPM and normal dispersion at first to create enough frequency chirping first. The pulse shape would also be broadened at the same time. However, the chirping can be enhanced before the pulse power is reduced to the linear range [164]. Besides, optical wave breaking could occur due to the combined effects of normal dispersion and SPM or XPM [166, 167]. It takes the form of the fast oscillation in the edges of the pulse. The optical wave breaking has some negative effects on the pulse compression since it may cause the phase distortions which could not be compensated by the quadratic compressor. As a result, the pulse could not be well de-chirped so that the compressed pulse is not that clean with possible two side lobes. The Raman scattering can also some negative influence the pulse compression, which may lead to residual energy in the wings [167].

Fig.3-4 illustrates the compression enhancement factor versus different T_0 when the input peak power is fixed at 12 kW in section 1 and 2 of the inline optical fibers structure. Fig.3-4 (a) shows the enhancement factor against when the input pulse T_0 is 100 fs. The overall trend of the enhancement factor increase as the section 1 length gets longer and decreasing afterwards. At first, the increasing trend may be attributed to more sufficient linear chirping in the section 1. The side peaks and the pedestal of the pulse could be suppressed so that more energy is transferred to the central peak. The highest peak power enhancement occurs when the section 1 length is about 5 cm. The pulse is compressed from 12 kW to almost 120 kW with the corresponding section 2 length of around 3 cm. With the further propagation in section 2, the

peak power could drop fast caused by the breaking up of the higher order soliton pulse. With the further increasing of the section 1 length, the enhancement factor tends to decrease. This may be attributed to the optical wave breaking or the confinement loss which is not ignorable but limited in section 1 due to the short length. In the real structure, a transition length between the section 1 and section 2 may not be obvious since the enhancement factor does not fluctuate much even when the length increases or decreases a little.

Fig.3-4. Highest enhancement factor achieved with the input pulse peak power of 12 kW and pulse half width T_0 of 100 fs (a), 200 fs (b), 300 fs (c) and 400 fs (d) when scanning the length of section 1 with the step of 1 mm.

When the input pulse T_0 increases to 200 fs, the enhancement factor has the similar trend as when T_0 is 100 fs, as shown in Fig.3-4 (b). The highest peak power enhancement happens when the pulse is compressed to about 164 kW with the section 1 and section 2 lengths are 6.6 cm and 4.5 cm. The higher compressed peak power is probably because of more energy in the pulse.

This is also confirmed by Fig.3-4 (c) and (d) when T_0 increases to 300 fs and 400 fs. The corresponding highest compressed peak powers are at 180 kW to 190 kW level respectively. The difference is that the increment of the compressed peak power is reduced, indicating more energy stored in the side peaks or the pedestal. Also, the required fiber lengths are shorter due to a shorter fission length.

3.4.2 Pulse compression with different peak power

The compression enhancement factor versus the section 1 length under different input pulse peak powers when T_0 is fixed at 200 fs, as shown by Fig.3-5, whose overall trend is similar to that depicted by Fig.3-4. The enhancement factor increases first as the section 1 length gets longer and decreases afterwards. The initial enhancement increasing could also be attributed to more sufficient chirping provided in the section 1. When the input peak power reaches 4 kW as shown by Fig.3-5 (a), the highest compression enhancement factor occurs at the section 1 length between 16 cm to 22 cm where the pulse is compressed from 4 kW to above 34 kW. Further increasing the section 1 length does not improve the peak power enhancement. The enhancement factor stays above 11 between around 7 cm and 11 cm of section 1 with the maximum at 8.4 cm when the input power rises to 8 kW. Higher compressed peak power could be obtained if the input power increases, as illustrated by the Fig.3-5 (c) and (d). This is also because of the higher input power. The enhancement factor still stays at high level even when the section 1 length changes a little which could mitigate the influence of the transition length. However, the acceleration of the enhancement factor growing is getting slow as the input peak power increase. The highest enhancement factors obtained in Fig.3-5 are 8.6, 11.8, 13.7 and 15 when the input power is 4 kW, 8 kW, 12 kW and 16 kW. This also indicates that more energy could not be stored in the main peak of the compressed pulse when increasing the input power.

This trend could be further clearly observed in Fig.3-6 (a). Similar with the Fig.3-5, the required fiber lengths are shorter when the input power is higher.

Fig.3-5 Highest enhancement factor achieved with the fixed input pulse T_0 of 200 fs and peak power of 4 kW (a), 8 kW (b), 12 kW (c) and 16 kW (d) when scanning the length of section 1 with the step of 1 mm.

Fig.3-6 (a) shows plot of the best peak power enhancement factor versus the input peak power with different input pulse widths. The plot illustrates more clearly about the compression trend versus the input peak power and pulse width. As presented in the plot, higher input peak power induced a high enhancement factor depicted by the solid curves. However the increment of the enhancement factor gets smaller. Besides, as is seen already, the longer input pulse width also benefits the pulse compression, leading to a higher enhancement factor. This increment also gets smaller as the pulse with further increases. For example, when the input peak power is fixed at 12 kW, the enhancement factor is increased to 9.9 from 13.7 when T_0 increases from 100 fs to

200 fs. When T_0 further increases to 300 fs, the enhancement factor only increases to 15.6. This increment becomes even smaller to 0.7 when T_0 becomes 400 fs. This could be observed from the limited difference between the solid cyan curve and the solid black curve.

(a)

(b)

Fig. 3-6. (a) Best peak power enhancement factor achieved vs. input peak power with various input pulse widths, T_0 , of 100 fs (blue), 200 fs (red), 300 fs (cyan) and 400 fs (black). The pulse compression is compared between the inline structure (solid lines) and the anomalous dispersion fiber only (dashed lines). (b) Temporal pulse evolution in the inline structure with the input peak power of 12 kW and input pulse width of 200 fs.

I also investigate feasibility of using only the section 2 for pulse compression without the first section. This was motivated to avoid high loss in the section 1. The chirp is provided by the SPM and the de-chirping is attributed to the anomalous dispersion. Usually, combining section 1 and 2 to compress the input pulse could result in a better performance, as seen in Fig.3-6 (a) where the solid lines show higher enhancement factors than the dash lines. However, in low power levels, this single anomalous dispersion optical fiber performs a little better than the two sections. For example, when the input power is 4 kW, the compressed pulse peak power is higher in a single anomalous dispersion PCF than in the inline structure. This could be attributed to relatively low SPM due to the low peak power. Thus the frequency chirping is not sufficient. Moreover, the high confinement loss and the possible loss in the transition part may also be harmful to the compression. Therefore, the pulse compression could be less efficient as compared to the direct compression in a single section 2 fiber. Nonetheless, the inline optical fiber structure outperforms when the input peak power increases.

I choose the pulse with the peak power of 12 kW and T_0 of 200 fs as the input pulse to illustrate the merits of the inline fiber structure. Fig.3-6 (b) shows the temporal pulse evolution with the power normalized in the inline structure. The best enhancement occurs when the lengths of the section 1 and the section 2 are 6.6 cm and 4.5 cm respectively. It can be clearly seen the pulse is temporally broadened in the initial stage in the section 1 due to the chirping induced by the SPM and the normal dispersion. When the pulse enters the anomalous dispersion section, it is rapidly compressed. The peak power of the compressed pulse is obtained to be about 164 kW, which is nearly 14 times higher than that of the input pulse. Although a high power enhancement is achieved, it should be also noted the compressed pulse still has side peaks and the pedestal which may have undesired influence on the supercontinuum generation.

3.5 Coherent supercontinuum generation

The coherent supercontinuum generation in the inline optical fiber structure was investigated with the optimized lengths of each section as discussed in the previous sections. The SC in the inline structure is also compared to SC achieved in the section 3 only to emphasize the importance of the role of the precedent sections. I select a peak power of 12 kW and pulse duration, T_0 , of 200 fs as an input pulse in order to conform to the pulse compression as discussed in the earlier content.

Fig.3-7 depicts the supercontinuum generation in only the section 3 fiber. The spectrum evolution is shown in Fig 3-7 (a). The spectrum is gradually broadened as the pulse propagates along the fiber. The broadening could be observed at first, but will not be obvious with the further propagation. The spectrum bandwidth is also limited due to the insufficient nonlinear interaction by the temporal peak power dropping. A spectrum is sliced at the fiber length of 15 cm since the further broadening is slowed down, as depicted by Fig.3-7 (b). The black curve in the figure represents the average spectrum of 200 independently generated spectra when the input random noise is considered. The 200 independently generated spectra are also shown by the grey shadow in the figure. The bandwidth of the spectrum is around 250 nm at a -20 dB level below the maximum, covering the wavelength from 1427 nm to 1676 nm. The spectrum has almost no grey shadow in this region, indicating that the supercontinuum generation is quite stable without considerable spectral intensity fluctuation in the presence of random input noises. The degree of the coherence, g_{12} , is also calculated according to Equation (2.20), also from the 200 pairs of independently generated spectra. The modulus g_{12} value stays close to 1 across the bandwidth range, demonstrating that the generated supercontinuum spectrum is highly coherent.

Fig.3-7. (a) Spectral evolution in only the section 3 fiber without a pre-pulse-compression. (b) The average spectrum (black curve) from 200 independently generated spectra (shown by the grey shadows) in consideration of input random noises sliced at the fiber length of 15 cm. (c) The below plot is the corresponding simulated g_{12} .

A spectrogram, shown by Fig.3-8, is also employed to characterize the generated spectrum depicted by Fig. 3-7 (b). A linear group delay variation with wavelength is clearly shown in the figure. It is noted that the pulse is temporally broadened with the peak power dropped to about 4 kW from 12 kW. The longer wavelength components are correlated with the pulse in the leading edge, whereas the shorter wavelength components are linearly associated with the pulse in the trailing edge. Therefore, the pulse is regarded to be linearly chirped. Although the highly coherent supercontinuum generation is obtained with this single normal dispersion fiber section, the bandwidth is limited to 250 nm. Hence I use the same pulse to investigate the supercontinuum generation in the inline optical fiber structure. The temporal pulse evolution in the section 1 and section 2 has been studied above.

Fig.3-8 Spectrogram of the supercontinuum generation depicted by Fig.3-7 (b).

Fig.3-9 illustrates the supercontinuum generation in the inline optical fiber structure, which fully demonstrates the merits of the structure. The peak power has been enhanced to about 164 kW from 12 kW in the first two sections. The spectrum evolution in the whole three sections is shown in Fig 3-9 (a). The roles of each section are clearly shown in the figure. The spectrum broadens moderately when the pulse propagates in section 1 (6.6 cm) and section 2 (4.5 cm). This corresponds to the pulse compression process. When the pulse enters the section 3, a sudden, fast broadening takes place and a wider bandwidth is obtained. As the pulse propagates, the spectrum almost maintains without obvious further broadening. However, the high confinement loss and the absorption in silica could possibly hinder the spectrum broadening if the section 3 fiber gets longer.

I sliced the spectrum using only 0.5 cm section 3 fiber shown by Fig.3-9 (b) since the spectrum was already fully broadened. The spectrum depicted by the black curve is also the average spectrum of 200 independently generated in consideration of the input random noises with the spectral intensity fluctuation shown by the grey shadow across the bandwidth. A near 1.3 octaves SC generation is obtained. The bandwidth of the spectrum is around 1260 nm, covering wavelengths from 900 nm to around 2160 nm, at a -20 dB level below the maximum. This is 5 times broader than that obtained with only the section 3 PCF shown by Fig. 3-7 (b). Besides, the spectrum is extended to above $2\ \mu\text{m}$ region, seldom seen in silica PCF. Moreover, the length is quite short, mitigating the loss in the section 3 taper. The limited spectral intensity fluctuation also demonstrates that the generated spectrum is also quite stable. The simulated degree of coherence g_{12} value is also almost close to 1 across the bandwidth range, demonstrating that the generated supercontinuum spectrum has a stable pulse to pulse phase relationship.

Fig.3-9. (a) Spectral evolution in the inline optical fiber structure. (b) The average spectrum (black) from 200 independently generated spectra, shown by the grey shadows, in consideration of input random noises sliced at the section 3 length of 0.5 cm. (c) The below plot is the corresponding simulated g_{12} .

The spectrogram, shown by Fig.3-10, is also calculated to better interpret the features of the obtained supercontinuum spectrum depicted by Fig.3-9 (b). The association between the temporal features and the spectrum is overall presented. It is noted that the peak power of pulse is brought down from around 164 kW to less than 25 kW in only 0.5 cm with some oscillation features. More importantly, it could be seen that the generated spectrum around the pumping wavelength region is higher than that in both sides. This limits the 20 dB bandwidth and leads to the unflatness in the spectrum. The spectrum at the pumping wavelength part is correlated with not only associated with the central main peak in the time domain, but also with the pedestal of the pulse, as clearly seen.

Fig.3-10 Spectrogram of the supercontinuum generation depicted by Fig 3-9 (b).

3.6 Chapter summary

In this chapter, an all fiber inline scheme based on silica PCF was proposed to achieve coherent supercontinuum generation after the peak power enhancement through an inline pulse compression. I presented both the PCF designs, fabrication tolerance and the design of the inline structure. With the input pulse with T_0 and peak power of 200 fs and 12 kW at the pumping wavelength of 1550nm to illustrate the merits of the inline PCF structure.

The all fiber inline can theoretically achieve:

- An almost 14 times peak power enhancement factor that achieve the peak power of about 164 kW from 12 kW.
- A broad supercontinuum spectrum of 1260 nm wide, covering wavelengths from 900 nm to around 2160 nm, at a -20 dB level below the maximum.
- High coherence of the generated supercontinuum spectrum through the numerical modelling considering the noise.

The simulation results shows that the inline structure is promising in the applications of the coherent supercontinuum generation.

Chapter 4:

Fiber fabrication and pulse compression

4.1 Introduction

The supercontinuum generation by normal dispersion pumping in PCFs faces a few the limitations. The temporal broadening of the pumping pulse rapidly brings down the peak power, thus lead to a limited nonlinear interaction for spectral broadening. Besides, high confinement loss due to the small structure and the possible water related absorption in silica are also influential especially in extending the spectrum to longer wavelengths above 2 μm . In chapter 3, I proposed an inline optical fiber structure based on the silica PCF consisting of 3 sections for coherent supercontinuum generation. The inline optical fiber structure was designed to enhance

peak power of the input pulse first for the subsequent coherent supercontinuum generation in the short last section.

Fig.4-1 Illustration of the two-section inline optical fiber structure.

In fabrication considerations, the normal dispersion sections including section 1 and section 3 are smaller than the anomalous dispersion section (section 2). Thus, the normal dispersion section can be inflated to make the anomalous dispersion section, or the anomalous dispersion section can be tapered to make the normal dispersion sections. Because the tapering process is a matured technology with a small number of fabrication parameters as compared to the inflation process, I decided to use the tapering process. In addition, although section 1 could be helpful for a higher peak power enhancement in most occasions, the simulation revealed that a fairly high compression can be achieved even only using the anomalous section 2, as illustrated by Fig.3-6 (a). Moreover, the dispersion of the fiber is sensitive to the small structure variation. Conducting tapering at both ends of a fiber to precisely control the dispersion is quite challenging. And this can also bring the risk of additional higher loss. Thus in order to illustrate

the merits and feasibility of the inline structure and avoid the fabrication difficulties, I first use two-section inline fiber structure for the supercontinuum generation, as illustrated by Fig.4-1. The pulse compression is in the anomalous dispersion section and the supercontinuum generation takes place in the normal dispersion taper. In this chapter, I mainly discuss the fiber fabrication, characterization and investigate the pulse compression in the anomalous dispersion fiber.

4.2 PCF fabrication and characterization

The transversal structures of the PCF designs were presented in Chapter 3. As shown by Fig.1-7, the influence of the cladding air hole layer on the fiber dispersion does not change the desired normal dispersion. This influence is even limited for the anomalous dispersion fiber with larger structure. Thus, I fabricated the PCF with 6 layers of the cladding air holes and the desired anomalous dispersion at the pumping wavelength of 1550 nm for experimental demonstration.

The target pitch size and cladding air hole diameter are $3\ \mu\text{m}$ and $1.2\ \mu\text{m}$, respectively. The fiber can be tapering to the pitch of $2\ \mu\text{m}$ and cladding air hole of 600 nm to shift the dispersion from anomalous to normal. The anomalous dispersion PCF can tolerate the fabrication error since the structure is larger. This has been discussed in Chapter 3. The normal dispersion taper has a smaller size. The fabrication of the taper can face the challenges that the dispersion dose not shift to the desired normal dispersion region or the confinement loss can be higher if the fabricated taper structure is smaller since the normal dispersion section is less tolerant to the fabrication errors. Therefore, strict controlling the structure of the taper is quite important.

4.2.1 Fiber fabrication

The fabrication of the PCF started with the capillary drawing followed by stacking. I used the HSQ300 tube to draw the capillaries for the air cladding holes. The HSQ300 silica glass owns high chemical purity, low bubble and inclusion content for industrial applications. The outer and inner diameters of the tubes were 25 mm and 19 mm respectively. A tube was loaded into the furnace in the drawing tower for capillaries. The temperature rose to 2060°C to soften glass for the dropping, and then fell to 1980°C for the capillary drawing to increase the capillary strength.

The feeding speed and the drawing speed were set to be 5.84 mm/min and 2 m/min to draw the capillaries with the outer diameter of 1.355 mm, which is determined based on the PCF design and applicable jacket tube size. A F300 rod was also employed to draw the solid core. The F300 glass is the high purity fused silica with low OH concentration. It is proper to be used as the core of the optical fiber. The rod is drawn down from 10 mm to 1.355 mm in diameter. The capillaries were carefully checked in size. Then those capillaries were stacked in a hexagonal lattice. In this process, the operation environment should be kept clean and any contamination should be avoided. Afterwards, the stack was inserted into a jacket tube with the outer and inner diameters of 20 mm and 16 mm for the preform drawing. One end of the preform was fused to collapse the stack by a dropping first. Then I cut a small opening about 9-10 cm to the fused position, so that the stack can be clamped by the tower and the vacuum can be applied through a self-made Teflon holder. The vacuum can merge the air between every two capillaries while leaving the air holes open for the further fiber drawing. The stack was loaded again to draw the preform. The dropping temperature was also 2060°C and the drawing temperature was 2030°C. The feeding speed and the drawing speed are 24 mm/min and about 0.6 m/min. The vacuum was

not applied until the monitored preform diameter was stable at about 3.8 mm. The applied vacuum pressure was about -27 kPa. Then, several preforms were obtained for the further fabrication. An image of the cane in the core area from a microscope is shown in Fig. 4-2. Compared with the stack illustrated by Fig.1-6 (a), the inter-capillary air vanishes while the cladding air holes are left. The air hole shape is hexagon with the pitch of $250\ \mu\text{m}$ and a side length of $190\ \mu\text{m}$, checked by a microscope.

Fig.4-2 The cross section image of a cane in the core area by a microscope.

Finally, the preform was drawn to fiber. The preform was inserted into another jacket tube with the outer diameter of 10 mm and inner diameter of 5 mm. A special designed holder was mounted at one side of the cane to apply the vacuum between the jacket tube and cane, as well as apply pressure to the air holes in the cane. The dropping temperature was $2100\ ^\circ\text{C}$. In the fabrication, when the vacuum was larger than -6 kPa, the space between the jacket tube and cane could not be fused. I used about -10 kPa for the vacuum. I gradually tried different temperatures, pressure and slightly adjusted the drawing and feeding speed. The feeding speed

was finally set to be 5 mm/min and the fiber was drawn at the speed of 17.6 m/min when the drawing temperature was 2002 °C. Higher temperature could lead to the shrinking, or even collapse, of the air holes, while low temperature might cause the tension high. Besides, 4 kPa pressure was needed in the fabrication in order to adjust the air hole diameter. The drawing tension kept at about 240 g. The monitored bare fiber diameter is 153 μm and will increase to 265 μm after being coated with a higher refractive index DeSolite 3471-3-14.

The scanning electron microscope images of the PCF were used to check the transversal structure of the fiber. Fig.4-3 (a) shows an overall view of the fiber structure. It is noted that the size of the cladding air holes in the outer layer is larger than that of the inner layer. This could be caused by the vacuum applied between the jacket tube and the cane in the final fiber drawing stage. The outer layer of air holes expanded more. A magnified detail of the fiber structure in the solid core area is depicted by the Fig.4-3 (b). The air holes are more identical. The measured average pitch size is 3.2 μm and the average cladding air hole diameter is about 1.4 μm .

Fig.4-3 The scanning electron microscope image of the fabricated PCF. (a) An overall view of the PCF. (b) A local view in the core area of the PCF.

4.2.2 Dispersion characterization

Fig.4-4 Dispersion measurement of the SMF using the phase retrieval based using the interferometric method described in chapter 1. (a) The measured interferogram (black solid curve) and the background spectra (red dash curve). (b) The recalculated $VS(\lambda)$ (black solid curve) and the cosine phase item after removing the influence of the visibility (red dash curve). (c) The retrieved phase (solid black curve) and the group delay time obtained (red solid curve). (d) The measured group velocity dispersion parameter D (black solid curve) and dispersion slope (red solid curve).

The dispersion of the fiber was measured using the phase retrieval based using the interferometric method described in Chapter 1. The experimental configuration is represented in Fig.1-8. The feasibility and accuracy of the proposed measurement approach is first tested

with a commercial single mode fiber. A 31.5cm long fiber was mounted in the tested fiber arm. The setup was adjusted to achieve high contrast interference. The interferogram was recorded by the optical spectrum analyzer and presented in Fig.4-4 (a). The red dash curves represent $I(\lambda)$ and $a(\lambda)I(\lambda)$. They were recorded separately when blocking the one arm. To retrieve phase information, $VS(\lambda)$ is obtained by using Equation (1.7), drawn by the black curve in Fig.4-4 (b). The red curve is obtained by using Equation (1.8) to remove the influence of visibility. Consequently, the phase term can be extracted from the red curve. The extracted phase in the SMF from the red curve in Fig.4-4 (b) is shown in Fig.4-4 (c). The group delay calculated by using (1.9) is depicted together. The minimum phase occurs at the wavelength of 1495nm, which corresponds to the zero group delay time, as shown by the red solid curve in Fig.4-4 (c). The group delay also has an inflection point at around 1312nm which indicates zero dispersion at the wavelength. The further retrieved dispersion curve by using Equation (1.11) in Fig.4-4 (d) confirms it. The results are in an excellent agreement with suppliers specifications regarding to the provided dispersion value, ZDW and dispersion slope at ZDW, showing good accuracy.

Then, for the measurement of the fabricated PCF, a 25.5 cm long fiber was mounted in the tested arm in the interferometer. The measured interferogram and two background spectra are shown by Fig. 4-5 (a). The less dense interference in the central part indicates a balanced optical path difference at the wavelength. I calculated the $VS(\lambda)$ containing the cosine phase item and the influence of the visibility according to Equation (1.7), depicted by black solid curve in Fig.4-5 (b). The amplitude of the $VS(\lambda)$ oscillation gets smaller towards the both sides. This is influenced by the imperfect visibility. The peaks and bottoms of the $VS(\lambda)$ were sought to get the upside and downside envelopes. The envelopes were obtained by a fitting of the searched peaks and bottoms. The influence of the visibility was removed according to Equation (1.8). The cosine phase item after removing the influence of visibility is plotted in the red dash curve

in Fig.4-5 (b). It is noted that the cosine phase item oscillates between -1 and 1 well, thus it is feasible to retrieve the phase.

Fig.4-5 Dispersion measurement of the fabricated anomalous dispersion PCF using the phase retrieval based using the interferometric method described in chapter 1. (a) The measured interferogram (black solid curve) and the background spectra (red dash curve). (b) The recalculated $VS(\lambda)$ (black solid curve) and the cosine phase item after removing the influence of the visibility item (red dash curve). (c) The retrieved phase (solid black curve) and the group delay time obtained (red solid curve). (d) The measured group velocity dispersion parameter D (red solid curve) and the simulated dispersion curve with the measured pitch and cladding air hole size using Polymode package (black solid curve).

The retrieved phase is illustrated by the black curve in Fig.4-5 (c). The minimum value there occurs at the wavelength of 1578 nm. At this wavelength, the interferometer is balanced with no optical path difference between the two arms, thus corresponds to the zero group delay time, shown by the red curve in Fig.4-5 (c). The subsequent dispersion curve was obtained using Equation (1.10). The measured dispersion is illustrated by the red curve in Fig.4-5 (d). It is noted the fiber has the anomalous dispersion at the measured region, as desired in the design. The group velocity dispersion parameter D at 1550 nm is 55.32 ps/(km×nm). The dispersion profile is approximately linear with the slope of about 0.05 ps/(km×nm²). I also used the Polymode codes to simulate the dispersion of the fiber with the measured the pitch and air hole size according the SEM image. The result is shown in Fig 4-5 (d) by the black dash curve. The simulated result generally matches well with the measured result. The ignorable difference between the simulation and the measurement result may be attributed to either the error in the measurement or the measured size error of parameters substituted to the simulation.

4.2.3 Background loss

The background loss was measured employing the conventional cut-back method. I used 120 meters long fabricated fiber for the background loss measurement. A broadband supercontinuum white light source was used for the measurement. The broadband light was launched into the fiber and the resulted spectrum was recorded in the OSA. The fiber was cut to 1 meter long to record the spectrum again. The background loss is evaluated by measuring the difference between the two spectra. The background loss is plotted in Fig 4-6. A typical loss at 1550 nm is 0.016 dB/m. The loss in the vicinity of this pumping wavelength stays at the below 0.2 dB/m except a peak around 1400 nm. This peak is attributed to the water related absorption in silica.

Fig.4-6 Measured background loss of the fabricated optical fiber.

4.4 Pulse compression in anomalous dispersion fiber

4.4.1 Source laser

A 1550 nm femtosecond pulse laser was used as the pumping source. The pulse width is tunable from nearly 1 ps to around 80 fs with the repetition rate of 20 MHz typically. The average power can go up to 500 mW. The output beam diameter is 1.5 mm with the beam quality factor $M^2 < 1.2$. The output beam is collimated in free space. The working seed current was set to be 4.45 A. The output light is a little chirped.

Optical autocorrelators can be used for the measurement of the duration of the ultrashort pulses with picosecond and femtosecond durations where the electronic apparatus would be too slow. An autocorrelator was used first to characterize the pulse FWHM duration of the femtosecond pulse laser against the amplifier pump current, shown by Fig.4-7 (a). The pulse width ranges from around 770 fs to 80 fs when the amplifier pump current is tuned from 0.8 A to 3.6 A. Higher amplifier pump current could lead to a shorter pulse width. Besides, the output power was measured and the result is depicted by Fig 4-7 (b). When the amplifier pump current

increases, a higher output power also increases. The output power varied from about 50 mW to approximate 550 mW when the amplifier pump current changes from 1 A to 3.55 A.

Fig.4-7 (a) Measured pulse width versus laser amplifier pump current by an autocorrelator. (b) Measured power versus laser amplifier pump current.

4.4.2 Pulse compression.

Fig.4-8 Setup for characterization of the pulse compression.

A 13.5 cm long anomalous dispersion fiber was chosen for the characterization of the pulse compression considering the existed condition for the setup building. The positive chirp is originated either from SPM in the fiber or the light source, while the negative chirp is provided by the anomalous dispersion. A configuration is illustrated by Fig.4-8. A tunable attenuator was placed before the first lens thus control the input pulse power. The beam was then coupled into the 13.5 cm long anomalous dispersion fiber by a lens. About 2 dB power dropping was observed at the output end of the fiber at the pumping wavelength. The power values mentioned below are all after the consideration of loss from the coupling. After the compression in the fiber, the output light was collimated by another lens. Finally the collimated beam was launched into the autocorrelator in a free space way for the measurement. The autocorrelation traces were recorded by an oscilloscope.

I first compared the pulse compression in the fiber with different input pulse widths. When the input power gradually increases, the pulse compression will be enhanced because of more sufficient chirp from SPM. Higher input power also reduces the fission length according to

$$L_{fiss} = \frac{L_D}{N} = \sqrt{\frac{\tau_0^2}{|\beta_2| \gamma P_0}}, \text{ thus the input power level is limited in order to achieve a best}$$

compression where the pulse is not broken up yet. Here the fission length should correspond to the fiber length. If the input pulse width is shorter, the power level should also be reduced in order to maintain the fission length, thus achieve the best compression. I recorded autocorrelation traces under different amplifier pump current with the proper input power for the best compression. I used the coupled power to express the power level in order to keep consistent with experiments for supercontinuum generation in the inline structure even if the coupling efficiencies are not the same.

Fig.4-9 shows the normalized autocorrelation traces of the compressed pulse where the best enhancement occurs in the fiber before the pulse breaks up. The amplifier pumping current varies from 1.7 A to 2.9 A, with the corresponding input FWHM pulse width from 571 fs to 200 fs. The upward plot in Fig 4-9 (a) depicts the compressed pulse when the input pulse width is about 571 fs with the amplifier pumping current of 1.7A. The pulse has a central compressed pulse with the FWHM pulse width of about 60-80 fs when 96 mW power was coupled into the fiber. However, it is also noted the two side peaks stand around the central pulse with a large pedestal. This is undesired since the two side peaks and the large pedestal stores considerable energy compared to the main peak of the pulse, resulting in a less efficient peak power enhancement through compression. In the anomalous dispersion optical fiber, this undesired feature in the compressed pulse is resulted by the nonlinear positive chirp and linear negative chirp which could not compensate fully with each other. The energy that stored in the main peak is estimated to be less than 30% of the total energy. This is not favorable for the subsequent supercontinuum generation. I further reduced the pulse width to 520 fs to see the temporal pulse by the autocorrelator. The pulse is depicted by the second plot in Fig.4-9 (b). The pedestal and the side peaks of the compressed pulse get reduced a little though compared with the first plot. This shows that the more energy was transferred to the main peak, though the main peak still store a low level energy. The pulse width of the central main peak in the compressed pulse stays the same, roughly 60-80 fs. The autocorrelation trace was measured when about 64 mW power was coupled into the fiber.

Fig.4-9 The autocorrelation traces of the compressed pulses with best enhancement by the anomalous dispersion fiber under input pulse width of 571 fs, 520 fs, 456 fs, 385 fs, 308 fs and 200 fs.

As seen in the figure, when the input pulse width was further reduced to 456 fs, 385 fs, 308 fs and 200 fs, whose autocorrelation traces are shown by the rest plots in Fig.4-9, the pedestal and the side peaks are much smaller. The two side peaks almost vanish when the pumping pulse width is 200 fs and the pedestal is also much reduced, showing that the compressed pulse is cleaner. Meanwhile, the compressed pulse width of the main peak will keep almost unchanged, which indicates that more energy is stored in the main peak. The main peak energy portion will increase to above 40% when the input pulse width is 455 fs. This portion can exceed 60% when the input pulse width is 200 fs. A clean compressed pulse is preferred in the supercontinuum generation since the pedestal could lead to a shape protruding peaks in the spectrum. However, the required power to achieve the best pulse enhancement decreased as the input pulse width gets shorter, which is not desired for the supercontinuum generation. This could be simply understood from the fission length calculation. The required coupled power dropped to about 37 mW at 385 fs pumping and could further decrease to around 18 mW when the input width was 200 fs. Therefore, the power of the compressed pulse could still be low though the pulse shape is cleaner. Another drawback is the low compression ratio. The pulse width of the compressed pulse maintains at the 60-80 fs though the input pulse varied. Therefore, the shorter input pulse width leads to a smaller compression ratio, as well as the peak power enhancement.

Previously, chirped mirrors are preferred for the pulse compression due to the linear opposite chirp that could be provided to better compensate chirp of the pulse, thus generating clean pulse. In the supercontinuum generation presented in [131] and [132], 15 fs input pulses were compressed to around 5 fs with the compression ratio of 3 by the chirped mirror. Optical fibers could also be used for pulse compression. A 4 km long non-decreasing anomalous dispersion fiber was used to compress the pulse from 3.8 ps to around 700 fs for supercontinuum generation pumping source [114]. However, hollow core optical fiber is preferred in pulse compression

due to the low nonlinearity, which could lead to unclean compressed pulse. A 5 ps input pulse was compressed to about 400 fs by using 15 m length of hollow core fiber [129, 130], followed by the spectrum broadening process. In this chapter, I used about 13.5 cm long MOF for compression. The pulse can be compressed from over 500 fs to 60-80 fs, though with the existence of the pedestal. This could be acceptable to demonstrate the inline fiber structure since the peak power of the input pulse is enhanced with a shorter pulse duration.

In order to facilitate the supercontinuum generation in the subsequent normal dispersion taper, better peak power enhancement is preferred. The possible solution could be that a linear pre linear chirp should be provided before launching the light into the fiber. This could be realized by the normal dispersion section 1 as described in Chapter 3. The pre linear chirp could be helpful to suppress the side lobes and the pedestal [164], thus more pulse energy could be in the main peak to achieve a higher peak power enhancement factor. However, the fabrication feasibility becomes a main challenge. As will be described in next Chapter, a tapering the anomalous dispersion PCF to normal dispersion PCF requires a very delicate control since the normal dispersion fiber with a small structure is extremely sensitive to fabrication errors. Thus conducting tapering in both ends deemed not practical. Another method to increase the input power with a shorter compressor fiber. Higher input power leads to a shorter fission length if the pulse duration is fixed, thus the required anomalous dispersion fiber is shorter. Higher power could be favorable for the nonlinear interaction.

The soliton fission appears easily when the peak power and the fiber length are not well balanced. I fixed input pulse width at 571 fs, 510 fs, 385 fs and 200 fs, respectively. The input power was gradually increased and the corresponding autocorrelation traces were recorded. The autocorrelation traces were normalized and formed pulse evolutions, as shown in Fig.4-10. When the input pulse width is 577 fs, it is noted that when increasing the power in the initial

stage, the pulse was gradually compressed, depicted by Fig.4-10 (a). The shortest pulse width occurred at the coupled pulse power of around 100 mW with the side peaks on both sides. This matches the power level of the compressed pulse depicted by Fig.4-9. When further increasing the coupled power, the pulse almost recovered to one peak at 125 mW with larger pulse width. However, the pulse would break up into a few individual peaks as the input power further increases.

Fig. 4-10 The normalized autocorrelation traces with different pumping power when the input pulse width is fixed at (a) 571 fs, (b) 510 fs, (c) 385 fs and (d) 200 fs.

When the input pulse width was 510 fs, the evolution of the pulse was faster with best compression occurs at a lower power. The pulse was compressed quickly first and the shortest pulse width occurred when the launched power was about 55 mW with side peaks. Then, the pulse would also evolve into one pulse and break up into several peaks as the power further increases.

The evolution could be even faster when the input pulse width further reduced to 385 fs and 200 fs, as illustrated in Fig.4-10 (c) and (d). The pulse broke up at a low power, 37 mW and 19 mW respectively. Besides, more sub peaks were generated at the high power due to a higher soliton order. The pulses all underwent a temporal recovery and breaking up after the best compression. The pulse evolution might indicate that in the supercontinuum generation in the normal dispersion section 3 the bandwidth might drop a little shortly after the best compression power, which could be attributed to the less peak power enhancement caused by this temporal recovering and breaking up.

4.5 Chapter summary

In this chapter, I first presented the fabrication of anomalous dispersion fiber and characterize the pulse compress in the fabricated fiber.

- The MOF with the pitch of $3.2\ \mu\text{m}$ and the average cladding air hole diameter about $1.4\ \mu\text{m}$ was fabricated using the stack-and-draw method.

- The fabricated MOF owns the desired anomalous dispersion with the dispersion of 55.32 ps/(km×nm) at 1550 nm with a low background loss lower than 0.2 dB/m around the pumping wavelength.
- Using a piece of fiber with the length of 13.5 cm, the pulse could be compressed to 60-80 fs when the input pulse duration varies between 571 fs and 200 fs.
- The soliton fission process was experimentally observed, which could be helpful to understand the pulse evolution in the fiber.
- The possible solution to improve the compression for the subsequent supercontinuum generation was discussed.

Chapter 5:

Taper fabrication and coherent supercontinuum generation

5.1 Introduction

Nonlinear interaction in the optical fibers can be used to generate the broadband light source for many applications, including precise frequency metrology [102, 103], light sources for optical communications [106, 107], ultrashort pulse generation [108, 109], etc. The supercontinuum generation by the anomalous dispersion short pulse pumping could yield broadband spectrum through the soliton dynamics. However, the generated spectrum is sensitive to the pumping noises, owning the degraded coherence and unstable feature of the spectral intensity fluctuation, which limit the application in the frequency metrology, ultra-short pulse compression, etc. Supercontinuum generation in the normal dispersion fibers is highly coherent and less sensitive

to the input shot to shot fluctuation. Therefore it is quite attractive for the applications requiring a high coherence.

In the previous chapter, the pulse compression in the anomalous dispersion section was investigated experimentally. In this chapter, I will investigate the supercontinuum generation in the subsequent normal dispersion section fabricated by a tapering process. I first present the taper fabrication process to achieve the normal dispersion from the anomalous PCF (section 2 in the inline structure). Subsequently, I investigate the supercontinuum generation in the inline structure under different pumping conditions that is consistent with the pulse compression discussed in Chapter 4. I also use the numerical method to model the supercontinuum generation and calculate the degree of coherence of the generated spectrum. Finally, in order to increase the applicable input power, I attempt to experimentally shorten the section 2 length for further investigation of the supercontinuum generation in the inline optical fiber structure.

5.2 Inline structure fabrication through tapering

The normal dispersion section in the inline optical fiber structure was fabricated by a tapering process. The drawn anomalous dispersion fiber owns the pitch size and cladding air hole diameter of $3.2\ \mu\text{m}$ and $1.4\ \mu\text{m}$. The targeted fiber taper pitch size is $2\ \mu\text{m}$ with the air hole size of $600\ \text{nm}$. In the fabrication of the inline fiber structure, one difficulty is to control the required parameters individually during the taper. In addition, fabrication tolerance is very tight for the tapering. A smaller tapered structure than required might result in a larger normal dispersion, and the same time a higher confinement loss which could possibly weaken the nonlinear interaction for the coherent supercontinuum generation. On the other hand, a little larger

tapered structure would also bring the potential issue that the dispersion might remain in the anomalous regime.

Fig 5-1 Examples of tapering profiles with the waist length of (a) 20 mm with transition length of 2.5 mm, (b) 20 mm with transition length of 2.5 mm, (c) 40 mm with transition length of 3 mm, and (d) 50 mm with transition length of 2.5 mm.

The anomalous dispersion PCF was heated by a CO₂ laser in a tapering machine to fabricate the normal dispersion taper. The anomalous dispersion fiber had a bare fiber diameter of 153 μm and was designed to be tapered to 104 μm for the normal dispersion, shrinking the pitch and air hole diameter for a normal dispersion. The heating power was selected to be about 15 W. Pulling speed of the motor is 0.1 $\mu\text{m}/\text{ms}$ without transversal rotation. Several measured taper sample profiles using the above conditions are shown in Fig.5-1. The samples have different taper waist lengths or transition lengths. The waist lengths are 20mm, 20mm, 40 mm and 50 mm with the transition length of either 2.5 mm or 3 mm. The measured taper diameters in X and Y directions depicted by the red and grey curves match well with the designed profile (the blue curve). The waists of the tapers are quite uniform within $\pm 2 \mu\text{m}$ variation. Besides, the tapering process is so consecutive that every taper could be stably done with good uniformity. However, a consecutive bare taper diameter alone does not ensure the targeted pitch size and air hole diameter. Compared with the transversal area of silica, the air hole area is quite small. Therefore, small variation of the air hole which might be influential in the fiber properties could not be perceived from the bare taper diameter. All the tapered fibers were examined in the scanning electronic microscope for further confirm the pitch and air hole sizes.

I chose one taper sample which was examined by a scanning electron microscope (SEM) shown by Fig 5-2 (a) and (b) for the experiment. The pitch and the cladding air hole sizes are scaled independently. Though the outermost layer air holes are slightly larger, the air holes are more identical in the core area as shown in the figure. The measured average pitch size is 2 μm and the cladding air hole diameter is 588 nm. The dispersion of the taper is determined using the Polymodes codes by substituting the measured pitch and air hole sizes. As shown by Fig.5-2 (c), the taper owns the desired normal dispersion for supercontinuum generation. The β_2 at 1550

nm is $25 \text{ ps}^2/\text{km}$. 1 cm long fiber taper was cut for the investigation of the supercontinuum generation.

Fig.5-2. (a) and (b) are the SEM images of the fabricated fiber taper. (c) shows the simulated dispersion parameter β_2 of the taper.

5.3 Supercontinuum generation

I first investigated the supercontinuum generation using the optical fiber inline structure consisting of 13.5 cm anomalous dispersion PCF and 1 cm normal dispersion. Hence the total length of the inline optical fiber structure is only 14.5 cm. In order to make sure that the best

compression occurs right before pulses propagate in the taper without pulse breaking up, the launched power should be consistent with that used in the pulse compression investigation in Chapter 4 at the same pumping pulse width. Besides, the supercontinuum generation was also investigated under different pumping pulse width and power level to observe the spectral evolution to better understand the pulse behavior.

Fig. 5-3 Setup for the supercontinuum generation. M1-M2: Silver mirrors. L1-L3: Lens. OSA: optical spectrum analyzer.

5.3.2 Supercontinuum generation in inline fiber structure

The inline optical fiber structure has 13.5 cm section 2 and 1 cm section 3. Using the inline silica optical fiber structure, the widest supercontinuum generation was obtained when the input pulse width is about 520 fs. I still use the coupled power to express the power level, keeping consistent with the convention in Chapter 4. The spectral bandwidth is determined at a -40 dB level from the maximum spectral intensity. The spectral evolution is plotted in Fig 5-4.

Fig.5-4 (a) and (b) shows the obtained supercontinuum spectrum when the coupled power is 23 mW and 39 mW respectively. It can be seen that SPM still dominate the nonlinear process with

its characteristic oscillation in the central region. The spectrum bandwidth was not fully developed since the input power was at the low level and the peak power enhancement through compression was not strong. The bandwidths of the two spectra are 140 nm and 445 nm respectively. The launched power was further increased to 56 mW, the spectrum was further broadened with the bandwidth of 645 nm shown by plot (c) in Fig.5-4. Except the central protruding SPM features, it is also noted that the power level on both sides of the central area rose which could be through the nonlinear process such as FWM and Raman scattering.

The maximum bandwidth occurred at the coupled input power of about 70 mW, which was close to the pumping power of the best compression with pulse width of also 520 fs represented in Chapter 4. The spectrum covers the region from 1070 nm to 2138 nm at a -40 dB level. This is almost one octave spanning. Previously, the coherent supercontinuum generation spectra in silica PCFs was in the below $2\ \mu\text{m}$ region, as seen in Table.2-1. It can also be seen that the central region is nearly 10 dB higher than the neighboring region due to the pedestal of the pulse. This can also limit the bandwidth. As discussed in Chapter 3, a clean pulse with no pedestal and side peaks is preferred for supercontinuum generation. The broadened spectrum on both sides of the central region might account for the nonlinear interaction including the FWM and Raman scattering. The Raman scattering extended the spectrum towards the longer wavelength side. Besides, the incomplete developed spectrum swings on the two sides region also indicated the compressed pulse power was not high enough.

I use the numerical modeling to simulate the supercontinuum generation process. The result is shown in Fig.5-5. In Fig.5-5 (a), the average spectrum illustrated by the black curve in subplot (II) is obtained from 100 pairs of the independently generated spectra depicted by the grey shadow when considering the input random noise. The average spectrum matches with the experiment result by the red curve. The grey shadows overlapped each other indicating that the

spectrum does not suffer from any significant fluctuation by different input noises. The spectrum was quite stable across the bandwidth. I also calculated the degree of coherence, g_{12} , according to Equation (2.20), shown by subplot (I) Fig.5-5 (a). The spectrum is highly coherent across the bandwidth. I also used the spectrogram to further interpret the phase of the spectrum in Fig.5-5 (b). It is noted from the spectrogram that the broadband spectrum was generated by the central main peak and the pedestal contributed to the central protruding part in the spectrum. Besides, the spectrum shows the linear chirped feature with the longer wavelength components generated by the leading edge of the pulse and the shorter wavelength components from the trailing edge of the pulse. The temporal pulse shape also confirms that the peak power was rapidly brought down in the taper.

When further increasing the input power, the measured spectra are depicted by (e), (f) and (g). The bandwidth of the spectra in (e) slightly decreased to 940 nm compared with that in (d). In this stage, the pulse is less compressed, corresponding to a pulse recovery or breaking up. As discussed in Chapter 4, the power would slightly drop in the anomalous dispersion section. Moreover, it could also be noted that the characteristic of SPM in the central region gradually becomes obscure since the high order soliton breaks up in the anomalous dispersion section.

Fig.5-4 Supercontinuum spectra generated in the inline PCF structure with the input pulse power of 23 mW (a), 39 mW (b), 56 mW (c), 70 mW (d), 75 mW (e), 91 mW (f) and 105 mW (g) when the input pulse width is 520 fs.

Fig.5-5 (a) (I) Calculated g_{12} of the generated spectrum depicted by Fig.5-4 (d). (II) Measured spectrum (red curve) and simulated spectrum (black curve). (b) (I) Calculated spectrogram of the supercontinuum generation. (II) (III): Simulated spectrum and temporal pulse.

I increased the input pulse width to 570 fs to investigate the supercontinuum generation. The spectra are shown in Fig.5-6. Same with the supercontinuum generation by 520 fs pumping, the power enhancement through pulse compression was not obvious initially. Therefore, the spectrum was not much broadened. The bandwidth depicted by plot (a) in Fig.5-6 was only 71 nm when 25 mW power was coupled into the inline structure. The spectrum was further broadened as the power level increased to 50 mW and 75 mW, depicted by plot (b) and (c). The input pulse was gradually compressed to achieve a higher enhancement in this stage. The spectrum had the maximum bandwidth with the coupled power of around 100 mW illustrated by plot (d) in Fig.5-6. The spectrum has a bandwidth of about 980 nm, covering the wavelength from 1097 nm to 2078 nm. The bandwidth was smaller than that of nearly 1070 nm depicted by plot (d) in Fig.5-4 though the input power was higher. The reason could be attributed to a less efficient pulse compression in the anomalous dispersion section since more energy was stored in the pedestal. It could also clearly observed that the SPM feature stood in the central spectrum. Besides, the central spectrum was also much higher than the neighboring region. The spectrum was quite stable with little fluctuation in the spectral intensity. However, with the further increasing of the input power, the bandwidth was slightly reduced to about 850 nm, shown in plot (e) in Fig.5-6. Similarly, this reduction of the bandwidth could also be accounted for either the restore of the pulse or the pulse breaking up in the anomalous dispersion section 2, which brought down the compressed pulse peak power.

Fig.5-6 Supercontinuum spectra generated in the inline PCF structure with the coupled power of 25 mW (a), 50 mW (b), 75 mW (c), 100 mW (d) and 125 mW (e) when the input pulse width is fixed at 570 fs.

Pulse width longer than 520 fs does not lead to a broader supercontinuum generation in this inline structure, while shorter input pulse widths does not increase the bandwidth compared to broadest spectrum obtained in Fig.5-4. Fig 5-7 and Fig 5-8 shows the spectra obtained with the input pulse width of 385 fs and 200 fs. The spectra behaved similar to previous two discuss in the initial stage of increasing the pumping power. The bandwidth gradually increased with the SPM characteristic in the central region. The best coherent supercontinuum generation spectra were obtained at the launched power of 43 mW and 17 mW respectively, which are illustrated by plot (c) in Fig.5-7 (c) and plot (a) in Fig.5-8. As discussed in Fig.4-9, cleaner compressed pulse could be obtained in section 2 for both situation when compared with the compressed pulse by 520 fs pumping. However, the applicable input power level was reduced. Thus, the peak powers of the compressed pulses were still at low level. This could limit the coherent supercontinuum generation, as seen in the figures. Obviously, the bandwidths of the spectra are much limited compared with that depicted by Fig 5-4 (d). The generated spectrum with the 385fs input pulse depicted by plot (c) in Fig.5-7 (c) spanned from 1186 nm to 2067 nm. The supercontinuum bandwidth was even much narrower when pumped with 200 fs, covering only 1428 nm to 1705nm. An interesting thing is that the differences between the central maximum power and the neighboring wavelength level are reduced in both case. This could be also attributed to smaller pedestals of the compressed pulse.

When further increasing the power, the spectra gets broad and narrow by turn a few times as the pulse restored to one peak and broke up. However, those spectra behaved more sensitive to the noises with the spectral intensity fluctuation, which could be clearly seen in the figures. Besides, the SPM feature was also getting obscure. This could show that the spectra were not broadened through SPM, thus might have a low coherence.

Fig.5-7. Supercontinuum spectra generated in the inline PCF structure with the coupled power of 12 mW (a), 29 mW (b), 43 mW (c), 62 mW (d), 78 mW (e), 95 mW (f), 110 mW (g), 134 mW (h) and 150 mW (i) when the input pulse width is fixed at 385 fs.

Fig.5-8 Supercontinuum spectra generated in the inline PCF structure with the coupled power of 17 mW (a), 31 mW(b), 34mW (c), 51 mW (d), 71 mW (e), 85 mW (f), 102 mW (g) when the input pulse width is 200 fs.

5.2.2 Supercontinuum generation in inline fiber structure with shorter section 2

The experimental results in 5.2.1 also encounter the limitation leading to the spectra that are not fully developed. One possible problem is the defective pulse compression in the anomalous dispersion section 2. The pedestal and the side peaks in the compressed pulse store considerable energy, so that the energy in the main peak is usually low. This harms the peak power enhancement, thus the nonlinear interaction in the normal dispersion taper. As discussed in Chapter 3, this could be improved by a pre-linear-chirp to generate a cleaner compressed pulse. The other reason is attributed to that only the low level power could be used in the input pulse in order to maintain one pulse to avoid fission in section 2. The length of the section 2, which can be also regarded as the indicator of the fission length for the pulse evolution, limits the input power. With the same pulse width, higher peak power could result in a shorter fission length. Thus, using a shorter anomalous dispersion section 2 might be beneficial in employing a higher input power. Therefore, I further shorten the anomalous dispersion section length to around 9 cm to investigate the supercontinuum generation. It should be clarified that the 9 cm length was chosen for comparison with the previous inline structure, but not determined by numerical optimization. This applicable input power was determined by the power that generated the spectrum before the bandwidth had a decreasing trend for the first time as the input power increased.

I used the 546 fs pulse to pump the shortened inline structure. It could be noted that that the spectrum generated by shorter inline structure (black curve in Fig 5-9 (a)) is broader compared with that obtained in the previous inline structure (red dash curve in Fig. 5-9 (a)) since the coupled

(a)

(b)

Fig.5-9 (a) Supercontinuum spectra obtained when the input pulse width of 546 fs. The coupled power of about 95 mW (black curve) and 65 mW (red dash curve) respectively. (b) Supercontinuum spectra obtained when the input pulse width of 520 fs. The coupled about 95 mW and 70 mW respectively. The black solid curves are the best spectrum obtained in the shortened inline structure while the red curves illustrated the spectrum in previous inline structure.

Fig.5-10 (a) (I) Calculated g_{12} of the generated spectrum depicted by Fig 5-9 (b). (II) Measured spectrum (black curve) and simulated spectrum (red curve). (b) (I) Calculated spectrogram of the supercontinuum generation. (II) (III): Simulated spectrum and temporal pulse.

power rose from about 65 mW to above 95 mW level. The bandwidth depicted by the black curve was 1064 nm, spanning from 1056 nm to 2120 nm at a -40 dB level from the maximum. This was broader than the 806 nm bandwidth by red dash curve. Further increasing the power could lead to a slight bandwidth reduction. The higher applicable input power also leads to a broader supercontinuum generation, as noted that the spectrum on both sides of the pumping wavelength rises slightly though unclean pulse with the pedestal could still exist. The difference between the maximum spectral intensity and the neighboring flat region was almost 17 dB.

The broadest spectrum was obtained when the input pulse width was fixed at 520 fs when the launched power was about 95 mW, shown by Fig. 5-9 (b). The spectrum spanned from 968 nm to 2158 nm, covering over 1 octave range. The bandwidth is also wider than that depicted by the red curve, the same plot as plot (d) in Fig.5-4. I also used the simulation to modeling the supercontinuum generation depicted by Fig. 5-10. The simulated spectrum generally matches with the experiment except for the difference in the longer wavelength side which may be attributed to the loss. I also calculated the degree of coherence. It illustrates that the generated spectrum is highly coherent. A detail view of the spectrum is given by the spectrogram in Fig 5-10 (b). As seen clearly, the spectrum is linear chirped across the bandwidth. Similarly, the longer wavelengths are generated by the leading edge of the pulse whereas the shorter wavelength corresponds to the shorter wavelength components. And the pedestal of the compressed pulse contributes to the central SPM protruding region.

In silica MOFs for coherent supercontinuum generation, few works reported the spectrum that could extends to above 2000 nm. The supercontinuum generation achieved in [110] covers the wavelength up to about 1500 nm by pumping 50 fs at 1050 nm to an all normal dispersion PCF. Similarly, another PCF was also designed to own all normal dispersion and generated the 800 nm spectrum extending to about 1400 nm by pumping at 1075 nm [129, 130], though the pulse

was pre-compressed to about 400 fs by a hollow core fiber. The power coupled into the fiber was no more than 1 W. Many other PCFs were designed for the shorter pumping wavelength [131, 132, 134, 136] through the design of the air hole structures. The pumping pulse duration were no more than 110 fs in these reports while the spectrum range stayed shorter than 1400 nm. Though some reports also used the pump at about 1550 nm with their designed MOFs [125-127], the bandwidth was limited since the pulse energy was low. In this work, the generated spectrum extended to above 2000 nm range with the pulse energy of about 5 nJ after a pre-compression to enhance the peak power with a short length of inline fiber structure, though the spectrum was not fully developed. This indicates the possibility to achieve the coherent supercontinuum generation in 2 micron range in silica fibers.

Further shortening the pulse width dose not lead to the broader supercontinuum generation since the applicable input power was lower in the inline structure. Fig.5-11 shows the coherent supercontinuum spectra that are measured when the input pulse width is adjusted to 500 fs and 456 fs respectively. The spectrum generated depicted by the black curves are also improved compared with those in the previous inline structure due to a higher applicable input power. The spectra cover the spanning of near 1070 nm and 1090 nm, also including the wavelength components above $2\ \mu\text{m}$.

Three-section inline fiber structure described in Chapter 3 should benefit the peak power enhancement through the pulse compression by suppress the pedestal and side peaks, thus the coherent supercontinuum generation. The investigation in the three-section structure is expected in the future work.

(a)

(b)

Fig.5-11 (a) Supercontinuum spectra obtained when the input pulse width is 500 fs. The launched power are 85 mW and about 50 mW. (b) Supercontinuum spectra obtained when the input pulse width is 456 fs. The launched power are 75 mW and about 60 mW respectively. The black solid curves are the best spectrum obtained in the shortened inline structure while the red curves illustrated the spectrum in previous inline structure.

5.4 Chapter summary

In this chapter, I first presented the fabrication of the normal dispersion fiber taper and the supercontinuum generation in the two section inline structure.

- The normal dispersion fiber taper was fabricated with the pitch size of the cladding air hole diameter shrunk independently to the desired the sizes.
- The coherent supercontinuum generation spanning from 1070 nm to 2138 nm was obtained at the input pulse width of 520 fs in with the inline fiber structure consisting of 13.5 cm anomalous dispersion fiber and 1 cm fiber taper.
- When section 2 is shortened to 9 cm, the coherent supercontinuum spectrum with the bandwidth of near 1200 nm, spanning from 968 nm to 2158 nm, was generated.

The measured spectra were generally broader than those obtained in the first longer inline structure under the same pulse width due to a higher applicable power.

Chapter 6:

Conclusion and Outlook

Supercontinuum generation has various applications as a broadband light source and has been widely studied in PCFs. By a short pulse pumping at anomalous dispersion region in a fiber, larger bandwidth could be expected in the generated spectrum. The spectrum is broadened through the soliton dynamics which leads to complex spectral structure. The generated spectrum is sensitive to the input shot to shot noises and the coherence degrades fast, which is attributed to the modulation instability. Whereas by pumping in normal dispersion region, the generated spectrum usually owns a high coherence since the modulation instability could be inhibited. The spectrum is broadened by SPM, FWM and Raman scattering, etc. The bandwidth is usually limited due to the peak power drop in the temporal broadening process. Previous, the dispersion was tailored in silica PCF to achieve the desired normal dispersion or all normal dispersion. Pulse compression was also involved by using a separate long anomalous dispersion fiber to

enhance the input pulse, where additional loss could be induced in the coupling. The smaller structure in these normal dispersion fibers could lead to high confinement loss, in addition to the water related absorption in silica. These also impeded the coherent supercontinuum generation in longer wavelength region, especially in above $2\ \mu\text{m}$ region.

In this work, an inline structure with a longitudinal variation based on the silica PCF is proposed for the highly coherent supercontinuum generation. The designed inline PCF structure owns three sections with a normal-anomalous-normal dispersion profile. The first normal dispersion section provides with pre-chirp for a better pulse compression in the subsequent anomalous dispersion section. The pulse is then enhanced through the compression for the coherent supercontinuum generation in the final normal dispersion section with a short length. In this all fiber inline structure, the length could be quite short, which mitigates the loss and benefits the spectrum broadening.

In chapter 3, the inline fiber structure was proposed and the supercontinuum generation in the inline fiber structure was theoretically investigated. The anomalous dispersion section owned the pitch and air hole diameter sizes of $3\ \mu\text{m}$ and $1.2\ \mu\text{m}$ respectively. The normal dispersion sections had the pitch size of air hole diameter of $2\ \mu\text{m}$ and $600\ \text{nm}$ respectively. The inline structure was designed to be fabricated by a tapering process. The sections lengths were determined according to the pumping condition. I used the input pulse with T_0 and peak power of $200\ \text{fs}$ and $12\ \text{kW}$ to illustrate the merits of the inline PCF structure. The lengths of section 1 and 2 were $6.6\ \text{cm}$ and $4.5\ \text{cm}$ in order to achieve high peak power enhancement. The input pulse was compressed to about $164\ \text{kW}$, achieving an almost 14 times enhancement. The supercontinuum spectrum was finally obtained with the bandwidth of $1260\ \text{nm}$ using only $0.5\ \text{cm}$ long section 3. The spectrum covered the wavelength components in above $2\ \mu\text{m}$ region where the water-related absorption in silica might be high. The spectrum was quite stable

without obvious spectral intensity fluctuation in the consideration of the random noises. Simulation also showed that the spectrum was quite coherent with the pulse linearly chirped. The spectral broadening in only the section 3 normal dispersion fiber was also investigated for comparison to illustrate the merits of the inline fiber structure with the same pumping conditions. The bandwidth of the generated spectrum was limited to only about 250 nm, much narrower than that in the inline fiber structure. This further proved the merits to use the inline optical fiber structure for coherent supercontinuum generation.

In Chapter 4, the pulse compression in the inline structure was experimentally investigated. The inline structure consisting of only section 2 and 3 was used to illustrate the merits of the inline fiber structure. The PCF with the anomalous dispersion was fabricated using the stack and draw method. The fabricated fiber had the pitch and cladding air hole sizes of $3.2\ \mu\text{m}$ and $1.4\ \mu\text{m}$ respectively. The dispersion of the fiber was measured using the interferometric method which showed that the PCF owned the desired anomalous dispersion. The pulse compression was investigated using 13.5 cm long fiber. The FWHM of the compressed pulse are about 60 – 80 fs with different input pulse widths varying from 600 fs to 200 fs. For longer pulse pumping, the required input power was also higher so as to achieve a better compression. Meanwhile, the compressed pulse also owns larger pedestals and side peaks which store much energy and limit the peak power enhancement. It was also observed that the soliton fissions as the input power increases. This helped to understand the pulse evolution and the subsequent supercontinuum generation in section 3.

In Chapter 5, fabrication of the inline structure of two sections through tapering and the investigation of supercontinuum generation was presented. The fabricated PCF was tapered with the pitch and cladding air hole shrunk independently to a $2\ \mu\text{m}$ and 588 nm respectively. Simulation showed that the taper owns the desired normal dispersion. The supercontinuum

generation was also investigated using the structure with 13.5 cm section 2 and 1 cm taper with different pumping conditions. The broadest supercontinuum generation was obtained when the pumping pulse width and coupled power were about 520 fs and 70 mW, spanning from 1070 nm to 2138 nm at a -40 dB from the maximum. By changing the pumping conditions, the spectral broadening was limited by either the applicable input power or less efficient compression. The section 2 length was further shortened for the investigation. The supercontinuum generation was broader with the spectrum spanning from 968 nm to 2158 nm when the pumping pulse width and coupled power were about 520 fs and 95 mW. The degree of the coherence and spectrogram were calculated to confirm that the two generated spectra were highly coherent and nearly linear chirped.

The work still needs the further improvement including:

- (1) A higher peak power enhancement through compression. The pre-chirp of the pulse is favorable for the compression by suppressing the side peaks and pedestal. Therefore, the section 1 fiber could be employed to yield cleaner pulse for a higher pulse enhancement. In addition, the designs of the structure could be optimized for a higher applicable input power.
- (2) A better taper dispersion. A small normal dispersion is more favorable for the sufficient nonlinear interactions for the spectral broadening. Therefore, the PCF design of section 3 could be further optimized.
- (3) A stable fabrication. The fabrication of the tapering to achieve the desired normal dispersion through the independent shrinking of the pitch and cladding air holes could be challenging. A little error could influence the dispersion since the structure of the normal dispersion section is small. Thus, a stable tapering process to control the dispersion is needed.

Glossary of acronyms

FWM	four wave mixing
FWHM	full width half maximum
GNLSE	generalized nonlinear Schrodinger equation
GVD	group velocity dispersion
HNLF	high nonlinear fiber
LMA	large mode area
MIR	mid infrared
MOF	micro-structured optical fiber
OPD	optical path difference
OSA	optical spectrum analyzer
PCF	photonic crystal fiber
SEM	scanning electron microscope
SMF	single mode fiber
SPM	self phase modulation
XPM	cross phase modulation
ZDW	zero dispersion wavelength

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