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Luo, Jiaqi

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UNIVERSITY**

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ULTRAFAST MID-IR

ULTRAFAST MID-IR FIBER LASER

LUO JIAQI

LUO JIAQI

**SCHOOL OF ELECTRICAL AND
ELECTRONIC ENGINEERING**

2019

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LUO JIAQI

SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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罗佳琪
.....
Luo Jiaqi

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

11.4.19
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Date

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Assco Prof Tan Eng Leong

Authorship Attribution Statement

This thesis contains material from 5 papers published in the following peer-reviewed journals in which I am listed as an author.

Chapter 2.4.1 is published as Biao Sun, Jiaqi Luo, Boon Ping Ng, and Xia Yu, "Dispersion-compensation-free femtosecond Tm-doped all-fiber laser with a 248 MHz repetition rate," Opt. Lett. 41, 4052-4055 (2016).

The contributions of the co-authors are as follows:

- Dr. Xia Yu provided the initial project direction and edited the manuscript drafts.
- Dr. Biao Sun designed the experiment and prepared the manuscript drafts.
- I performed the experiment and data collection and analysis. And I participated in writing the manuscript.
- Dr. Boon Ping Ng reviewed the manuscript.

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- Dr. Xia Yu provided the initial project direction and edited the manuscript drafts.
- Dr. Biao Sun designed the experiment prepared the manuscript drafts.
- I co-designed the study with Dr. Biao Sun and performed the experiment, collected and analyzed the data. The main the results including pulse duration, power and spectrum were measured by me.
- Dr. Zhiyu Yan and Mr. Kun Liu assisted in the data collection.
- Dr. Junhua Ji, Dr. Ying Zhang and Prof. Qi Jie Wang reviewed the manuscript.

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The contributions of the co-authors are as follows:

- Dr. Xia Yu provided suggestion along the project and edited the manuscript drafts.
- Dr. Biao Sun designed and initialized the project, conducted the experiment and prepared the manuscript drafts.
- I conducted the data analysis for experimental results optimization. I performed the simulation for ultrafast pulse evolution. I participated in the experiment for dispersion precision control. I also revised the manuscript.
- Dr. Ying Zhang and Prof. Qi Jie Wang reviewed the manuscript.

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- I designed and conducted the experiment, analyzed the results and simulated the study. I also prepared the manuscript.
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- Dr. Junhua Ji assisted the results analysis and revised the manuscript.
- Prof. Eng Leong Tan and Prof. Qi Jie Wang reviewed the manuscript.

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- Dr. Xia Yu provided the initial project direction and edited the manuscript drafts.
- I designed the study, performed all the laboratory work including the ultrafast fiber amplifier, soft glass fiber supercontinuum generation, and

FROG/spectrum measurement. I also conducted the numerical simulation and wrote the manuscript draft.

- Dr. Sun Biao, Mr. Jiayun Liu, and Dr. Zhiyu Yan provided valuable suggestions for the experiment, discussed the results and revised the manuscript.
- Dr. Nanxi Li, Assoc. Prof. Eng Leong Tan and Prof. Qi Jie Wang reviewed the manuscript.

11/04/2019

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Date

马陆强

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[Input Name Here]

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Summary

Ultrafast fiber lasers have attracted great interest due to their wide applications, including ultrafast spectroscopy, nonlinear microscopy (multi-photon microscopy and time-resolved coherent anti-Stokes Raman scattering microscopy), and chemical/biomedical diagnostics. While ultrafast fiber lasers at 2 μm are attracting great attentions for their applications in many research fields, such as laser therapy, environmental gas detection, polymeric material processing and mid-IR source generation, the broad emission spectra of thulium-doped fibers (TDF) make them ideal candidates for ultrafast pulse generation in this wavelength region.

However, the key challenges of generating high power ultrafast 2 μm fiber laser are dispersion management and nonlinearity control. Different with the solid-state laser that the light propagates in free space, fiber lasers confine the light in fiber cores. Due to the long active length and tight confinement, the influence of the fiber dispersion and nonlinearity on the laser is not negligible. Moreover, due to the nature of silica, the standard fibers have a much larger anomalous dispersion at 2 μm , compared with that at 1 μm and 1.5 μm , and only several types of dispersion compensation fiber with small tiny cores are commercially available. The high power laser generation is limited by the fiber core size. The core diameter of the conventional step-index TDF is limited to 25 μm . And this fiber is normally a few-mode fiber, which degrades the beam quality and amplification stability. In this thesis, the experimental and theoretical study against these challenges is presented. It covers the mode-locked oscillator, fiber amplifier, and pulse compressor.

We designed a new hybrid fiber device to generate compact and dispersion-compensation free ultrafast mode-locked oscillators. The device integrates the function of the optical coupler, the polarization sensitive isolator and the wavelength division multiplex. Normally, TDF oscillators work in the soliton region, due to the anomalous dispersion for most single mode fibers at 2 μm . In soliton region, the minimum pulse width is determined by the net cavity dispersion. Thus, without dispersion compensation fibers, shrinking down the cavity length is important to generate ultrafast pulses. The cavity length is shrunk down to 80 cm. Pulses with 330 fs are generated even without dispersion compensation. The mode locking mechanism is based on the nonlinear polarization evolution (NPE) which provides simple oscillator

configuration and sub-picosecond pulse width. Moreover, the Lyot filter effect in the NPE cavity, enables the laser wavelength tuning.

Further pulse compression is investigated in an all-fiber compact system in Chapter 3. We propose an all-fiber sub-100 fs laser by properly controlling the dispersion and nonlinearity of a fiber chain. The laser with 65 fs pulse width and > 160 nm spectral width is obtained. The simulation based on nonlinear Schrödinger equation is carried out to investigate the laser formation and evolution. For the less than 10-cycle $2\text{ }\mu\text{m}$ laser generation in the all-fiber configuration, the work in literature requires multistage amplifiers and nonlinear compressors. We simplify the setup significantly.

A novel compact chirped pulse amplification (CPA) system is constructed to achieve the pulse energy scaling. The system uses the chirped fiber Bragg grating based stretcher, the large mode area thulium-doped photonic crystal fiber based amplifier and the chirped volume Bragg grating based compressor to achieve high energy pulses in a compact configuration. The selections of pulse stretcher, fiber amplifier and pulse compressor of the all-fiber CPA design are analyzed.

This thesis is not limited to the demonstration of TDF $2\text{ }\mu\text{m}$ lasers. It also covers mid-IR source generation pumped by the TDF laser. Based on the nonlinear phenomena including the self-phase modulation, soliton fission and Raman induced frequency shifting, the laser wavelength can extend and red-shift to mid-IR range. A tunable laser with $1.98\text{ }\mu\text{m}$ to $2.31\text{ }\mu\text{m}$ wavelength range and sub-200 fs pulse width is demonstrated. Thanks to the Raman induced frequency shifting, the tunable wavelength range exceeds the TDF gain spectrum. By optimizing the seed chirp, a record conversion efficiency up to 97% is acquired. A supercontinuum source with flat spectrum is also demonstrated. The supercontinuum generation in a ZBLAN fiber pumped by the femtosecond TDF laser is demonstrated for the first time. Thanks to the femtosecond pump laser, the supercontinuum has the spectral flatness of 10 dB over 1390 nm from 1940 to 3330 nm.

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List of Abbreviations

AOM	acousto-optic modulator
ASE	amplified spontaneous emission
CBC	coherent beam combining
CFBG	chirped fiber Bragg grating
CPA	chirped pulse amplification
CR	cross relaxation
CVBG	chirped volume Bragg grating
DCF	dispersion compensation fiber
DC-TDF	double-clad TDF
DW	dispersive wave
EDFA	erbium doped fiber amplifier
Er	erbium
FROG	frequency resolved optical gating
FTL	Fourier transform limited
fs	femtosecond
FSR	free spectral range
FWHM	full width at half maximum
GDD	group delay dispersion
GLE	Ginzburg-Landau Equation
HCF	hollow core fiber
HHG	high harmonic generation
HNLF	highly nonlinear fiber
HRM	highly reflected mirror
HWP	half wave plate
LMA	large mode area
MOPA	master oscillator power amplifier
MI	modulation instability
MID-IR	mid-infrared
NA	numerical aperture
NLSE	nonlinear Schrödinger equation
NPE	nonlinear polarization evolution
OC	optical coupler
OSA	optical spectrum analyzer

PC	polarization controller
PCF	photonic crystal fiber
ps	picosecond
PSISO	polarization sensitive isolator
QWP	quarter wave plate
SA	saturable absorber
SAP	stress applying parts
SEM	scanning electron microscope
SPM	self-phase modulation
SRS	stimulated Raman scattering
SSFS	soliton self-frequency shift
TBP	time-bandwidth-product
TDF	thulium-doped fiber
TFP	thin film polarizer
THDF	thulium-holmium co-doped fiber
TOD	third order dispersion
UHNA	ultra high numerical aperture
WDM	wavelength division multiplexer
XPM	cross-phase modulation
YDF	ytterbium doped fiber
ZBLAN	ZrF ₄ -BaF ₂ -LaF ₃ -AlF ₃ -NaF
ZDW	zero dispersion wavelength

Chapter 1 Introduction

1.1 Background

The field of fiber lasers grows rapidly in the past decades. From 2014, fiber lasers surpassed the CO₂ lasers, became the most popular lasers in the industrial market [1]. According to the report of the worldwide market for lasers 2018 [2], the annual industrial laser revenues from fiber lasers was US\$2039 million in 2017, around 47% of the total industrial laser revenues. And this value is expected to continuously grow in the following year. Benefit from the high efficiency, compact and robust system, and good beam quality, the fiber laser challenges the dominance of traditional laser technologies, such as CO₂ lasers and diode-pumped Nd:YAG lasers.

The field of fiber laser was born in 1961 [3]. Elias Snitzer demonstrated the world's first fiber laser in Barium crown glass with Nd³⁺. Three years later, the first fiber amplifier was developed by Charles J. Koester and Elias Snitzer [4]. A 47 dB gain was achieved in a 1-m long fiber. However, most scientists considered that fibers were not suitable for communication as these early fibers were extremely lossy (attenuation > 1000 dB/km). A revolution of fiber optics happened in 1966. Charles Kuen Kao and George Hockham theoretically proved that the high attenuation loss in fiber was due to the impurities in glass [5]. The loss of silica fiber could be dramatically reduced to no more than 20 dB/km by removing these impurities. Several scientists from Corning Glass Works experimentally realized this goal in 1970 [6]. They achieved single-mode fibers with 20 dB/km attenuation at 633 nm. From then on, optical fibers were deeply studied and widely applied.

In the first stage, the fiber lasers were pumped by the flashlamp. However, it was challenging for a gain fiber to absorb and store pump energy. So the efficiency and output power was very low. In 1974, Julian Stone and Charles Burrus made an important step to improve the performance [7]. They changed the pumping technology by using diodes to core-pump fiber lasers. This direct-core-pumping geometry is a limitation due to its requirement of single transverse mode laser diodes to allow efficient pump power launch into the doped single mode fiber core.

The evolution of high-power fiber lasers really took off in 1988, after the demonstration of the concept of cladding pumping through a double-clad fiber structure [8]. The signal still propagates in the rare-earth-doped fiber core to maintain the good beam quality, but the pump light is confined in the inner cladding by lower refractive index outer cladding. The pump light partially overlaps with the core and is absorbed by the rare-earth ions. Compared with the core, the inner cladding has much larger area and higher numerical aperture (NA). That is, lots of modes can be supported. The high power diode source with poor beam quality can be launched to fibers efficiently. Thanks to this innovative milestone, the development of high power fiber laser increased rapidly.

Nowadays, fiber lasers attract many interests in industrial, medical and scientific areas. They can take the place of the traditional bulk solid-state or gas lasers and have superior performance in several perspectives.

Fiber lasers are compact and robust. Fibers can be coiled to very small footprint, so fiber lasers can be much more compact than bulk lasers. The light is confined inside and protected by fiber claddings; no alignment is needed, and the laser is minimally affected by the ambient conditions, such as mechanical vibration and temperature variation.

The larger surface area to volume ratio makes fiber laser virtually unaffected by the thermal issues. The active region for fiber is much longer than that of solid-state or gas laser. Thus, it is relatively easier for fiber lasers to achieve high average power.

In the free-space bulk lasers, all modes can exist without aperture [9]. However, the laser modes are controlled by the design properties in fibers. The unwanted modes can be moved out by proper design of fiber structure and dimension. The beam quality can be close to diffraction-limited.

1.2 Motivation

The active medium of fiber lasers is the rare-earth doped ions. The common dopants are praseodymium (Pr), neodymium (Nd), ytterbium (Yb), erbium (Er), thulium (Tm), and holmium (Ho), corresponding to a different wavelength range of laser emission. Considering the transmission attenuation, the cost and quantum defects, the Yb-doped fiber (YDF) laser working at 1 μm and the Er-doped fiber laser operating at 1.5 μm are dominant in the laser

material processing markets and the optical communication area, respectively. However, for some specific applications, the performance of lasers at 2 μm wavelength range is more outstanding than lasers at 1 μm or 1.5 μm .

Polymer welding using fiber laser is common in industrial application. For some materials, the absorber is required for efficient welding by using YDF lasers due to the low material absorption at 1 μm [9]. The use of absorber may complicate the process and increase the manufacturing costs. In addition, due to the toxicity of the absorber, sometimes it is forbidden for use in biomedical applications. On the contrary, 2 μm lasers can be absorbed by the materials directly without the absorber [10].

The water absorption peaks at 2 μm region make such lasers very useful for medical applications [11]. Due to the strong absorption in water, the main constituent of biological tissues, substantial heating of small areas is achieved. This allows for very precise cutting of biological tissue. Additionally, the bleeding during laser cutting is suppressed by coagulation; this makes 2 μm lasers ideal for many surgical procedures.

Fundamental science is another important application area for 2 μm lasers, which have much longer wavelength than visible and near infrared lasers. The frequency conversion through nonlinear processes can benefit from 2 μm lasers. One example is the high harmonic generation (HHG) [12] that the extreme ultraviolet or soft X-ray source is generated through the high harmonics of intense lasers. The cut-off energy of HHG is proportional to the input laser peak intensity and wavelength [13]. Thus using 2 μm lasers as the pump have the potential to achieve higher HHG cut-off energy. In the other direction, referring to the wavelength, 2 μm lasers are also suitable for longer wavelength generation in mid-infrared (mid-IR) range. Pumping close to 2 μm results in both an extension of bandwidth and an increase of conversion efficiency towards mid-IR wavelengths [14].

Besides the laser wavelength, the ultrafast pulse width is another crucial factor. No matter for precise manufacturing in industry or micro-surgery for bio-tissues, ultrafast lasers can have better performance compared with long pulses or continuous wave. The ultrashort pulse width leads to higher resolution and lower thermal effects. In scientific application field, the frequency conversion based on nonlinearity is a laser intensity dependent process. With the same pulse energy, the shorter pulse width leads to higher peak intensity.

Meanwhile, ultrafast pulse lasers are powerful tools to observe some of the fast processes in nature and study matters under extreme physical conditions. Based on these, two Nobel prizes have been rewarded in the ultrafast optics region: the observation of molecules' transition states [15] and optical frequency combs for metrology [16]. Furthermore, the Nobel prize in physics 2018 is awarded for the method of generating high-intensity and ultrashort pulse, chirped pulse amplification [17].

For the rare-earth-doped fibers, both Tm-doped fibers (TDF) and Ho-doped fibers (HDF) lasers work at 2 μm range. But the emission spectrum of TDF (1.7 μm to 2.1 μm) is twice as broad as that of HDF (1.95 μm to 2.15 μm) [18]. Meanwhile, TDF can be pumped by laser diodes directly, and HDF is pumped by the TDF laser usually. Thus, TDF is more suitable for high power ultrafast 2 μm fiber lasers.

1.3 Objectives

The thesis is devoted to investigate high energy ultrafast lasers at 2 μm range in a compact system. It covers:

- (i) designing and developing ultrafast all-fiber TDF laser oscillators to achieve hundreds femtosecond pulse width;
- (ii) amplifying and further compressing the pulses from the oscillator in an all-fiber configuration to investigate the nonlinear pulse propagation dynamics in both passive and active fibers;
- (iii) achieving pulse energy of hundreds micro-joule level in a chirped pulse amplification (CPA) system to understand the energy extraction, nonlinearity control, ASE management and pulse compression in CPA system;
- (iv) using the ultrafast TDF laser as pump to extend the wavelength to mid-IR range to explore the new wavelength generation.

1.4 Major contribution

The major contributions of this Thesis are listed as:

- We developed an all anomalous dispersion fiber ring cavity based on a hybrid device integrating function of optical coupler (OC), polarization sensitive isolator (PSISO) and

wavelength division multiplexer (WDM). It was a dispersion-compensation-free solution for 2 μm lasers ultra-compact oscillator design with sub-500 fs pulse width. The fiber-based Lyot filter effect enabled the oscillator wavelength tuning. The ultra-compact cavity design attributed to a broadly tunable range. To the best of our knowledge, the tunable range from 1867 nm to 2010 nm is the widest tunable range obtained from an ultrafast TDF laser.

- We proposed an all-fiber TDF CPA system to scale the pulse energy to hundreds of micro-joules. In this CPA, we used the double-pass configuration in the pre-amplifiers to improve the gain performance and reduce the noise. The power amplifier stage was based on a large mode area (LMA) thulium-doped photonic crystal fiber (PCF). Pulses with up to 384 μJ energy were delivered. For our best knowledge, this is the highest pulse energy achieved from an all-fiber TDF CPA laser. Two chirped volume Bragg gratings worked as the compressor to shrink down the footprint of the compressor setup to 45 cm $\times$ 45 cm.
- The highest conversion efficiency up to 97% was achieved in Raman soliton lasers. The chirp value of the input pulse affects efficiency of the energy transfer to the Raman solitons. We optimized the chirp value by using a dispersion compensation fiber (DCF), which was verified by our simulation. Moreover, this Raman soliton laser had a widely tunable wavelength range from 1.98 μm to 2.31 μm . The achievable longest wavelength was limited by the cutoff of the silica material.
- We first demonstrated the mid-IR supercontinuum generation in a ZrF₄-BaF₂-LaF₃-AlF₃-NaF (ZBLAN) fiber pumped by a femtosecond TDF laser. Benefiting from the femtosecond pump, the supercontinuum spectrum was flat. The 10 dB bandwidth covered from 1940 nm to 3330nm. Furthermore, the femtosecond pulse width allows relative low pump power (sub-watt level). It requires less stringent specifications for all the optical components and the mid-IR waveguide.

1.5 Organization of this Thesis

After the introduction of history and application in Chapter 1, Chapter 2 provides the development and study of mode-locked fiber lasers. The principle of nonlinear polarization evolution (NPE), one of the passive mode-locking method, is described. Then, the TDF oscillators based on NPE are investigated. With or without dispersion management, femtosecond (fs) ultrafast lasers can be generated. The oscillators are further used as seed in the following experiments.

Chapter 3 studies two compression techniques of 2 μm ultrafast lasers in the all-fiber configuration. It details the experiment that pulse compression and amplification simultaneously in a one-stage all-anomalous TDF amplifier firstly. Then describes the sub-100 fs pulse generation through nonlinearity and dispersion management in a fiber chain. The simulation that investigates and verifies the pulse evolution in the fiber chain is also presented.

The application of the ultrafast TDF lasers to generate mid-IR sources is explored in Chapter 4. The flat supercontinuum resulted from the enhanced self phase modulation (SPM) process in femtosecond regime is presented. The Raman soliton laser with tunable wavelength and femtosecond pulse width is generated through the process of soliton self-frequency shift. The high conversion efficiency by optimizing the chirp of input pulses is discussed.

The high energy ultrafast lasers are presented in Chapter 5. The system based on CPA process is introduced. The LMA Tm-doped PCF based amplifier and the chirped volume Bragg grating (CVBG) based compressor is described in detail separately.

Chapter 6 summarizes the preceding chapter and draws conclusion of this thesis. The recommendation of future work is discussed.

Chapter 2 All fiber mode-locked oscillator based on NPE

2.1 Introduction to mode-locked fiber laser

Mode-locking is a general approach to generate ultrafast optical pulses in pico/femto-second time scale. Fundamentally, these ultrafast pulses in time domain result from mode locking between different longitude modes in frequency domain. Mode-locking refers to the longitudinal modes in the laser cavity with a fixed phase relationship. In a laser cavity, the total electrical field can be expressed as [19]:

$$E = \sum E_m = \sum A_m \exp \{-i[(\omega_0 + m \cdot \Delta\omega)t + \varphi_m]\} \quad m = 0, \pm 1, \pm 2 \dots \quad (2.1)$$

where m is the number of modes, A_m and φ_m is the amplitude and phase of m_{th} mode, and $\Delta\omega$ is the angular frequency difference between two adjacent modes. The number m is related to the gain bandwidth of the active medium and the laser cavity loss. $\Delta\omega$ is determined by the cavity length L and the refractive index n in a fiber laser cavity.

$$\Delta\omega = \omega_m - \omega_{m-1} = 2\pi c/L \quad (2.2)$$

For a single longitudinal mode, it corresponds to continuous wave in time domain. Pulses can be generated if numbers of modes are phase-locked. That is, the phase difference for two adjacent modes is constant.

$$\varphi_m = \varphi_0 + m\Delta\varphi \quad (2.3)$$

For simplifying the calculation, the amplitude A_m for each mode is assumed the same. Then the total electrical field is:

$$E = A_m \exp [-i(\omega_0 t + \varphi_0)] \sum \exp [-im(\Delta\omega t + \Delta\varphi)] \quad m = 0, \pm 1, \pm 2 \dots \quad (2.4)$$

The summation of the electrical field is:

$$E = A_m \exp [-i(\omega_0 t + \varphi_0)] \frac{\sin[\frac{2m+1}{2}(\Delta\omega t + \Delta\varphi)]}{\sin[\frac{1}{2}(\Delta\omega t + \Delta\varphi)]} \quad (2.5)$$

Consider the situation: there are 11 longitudinal modes ($m = 5$) with the same amplitude. Figure 2.1 shows the light intensity ($I = |E|^2$) in time domain in two cases: the phase of the 11 modes is random (Figure 2.1(a)) and the 11 modes are phase-locked (Figure 2.1(b)). The in-phase modes in frequency domain form the pulse train in time domain.

Figure 2.1 The light intensity in time domain: (a) modes with random phase and (b) modes with fixed phase relationship

Referring to the formation mechanism of the mode-locking, the techniques of mode-locking are classified into active mode-locking and passive mode-locking. For active mode-locking, active elements are involved in the cavity to induce a periodic modulation. The periodic modulation enforces the fixed phase relationship for each mode. As the external signal from active elements is electronic, the performance of active mode-locking relies on the speed of the electronic signal. On the contrary, no external signal is needed in the passive mode-locking. The pulse self-modulates in the cavity. Compared with active mode-locking, this all-optical technique enables much shorter pulse width.

In the passive mode-locking laser, no external signal to enforce the mode in-phase. A saturable absorber (SA) is usually required to achieve the mode-locking. The initial pulses are started from Q-switched-like noise spikes. Several modes may be in-phase and form pulses in the time domain. The SA shortens and stabilizes the initial pulses. The absorption of the SA and the pulse intensity are in inverse proportion. The high-intensity parts experience lower loss and the SA absorbs more for the low-intensity parts. The SA can help to keep and narrow the pulses due to its nonlinear interaction with pulses. Figure 2.2 illustrates the pulse shortening process due to the SA. The center of the pulse with high peak intensity experiences positive net gain and is amplified during the round trip in the cavity. Simultaneously, the wing of the pulse

suffers higher loss due to the low intensity. Therefore, the pulses with high peak power are formed in the cavity.

Figure 2.2 The illustration of the pulse shortening process due to the SA

2.2 Passive mode-locking based on NPE

2.2.1 NPE in optical fibers

The single mode fiber (SMF) can actually support two orthogonal polarization modes. Ideally, the conventional non-polarization maintaining optical fiber is cylindrically symmetrical. The effective refractive index is the same in the two orthogonal directions. The two polarization modes would not couple to each other. In fact, however, limited by the manufacturing process and material characteristics of fibers, there is a random variation in core shape and stress-induced anisotropic along the fiber, resulting in fiber birefringence. The fiber birefringence refers to the different effective refractive index in two orthogonal directions. The axis with smaller effective refractive index is called the fast axis, as the light velocity is larger. In contrast, the light on the axis with larger refractive index has lower velocity and is therefore called the slow axis.

When the incident light to fibers is a laser pulse or spiky noise in a laser cavity, the high peak power would induce the nonlinear effects, such as SPM and cross-phase modulation (XPM). And the polarization evolution would be affected by the nonlinear effects. The evolution can be explained by the coupled nonlinear Schrödinger equations (NLSE) [19]. If only nonlinearity is considered, the coupled NLSE for linear birefringence fibers can be expressed as:

$$\frac{\partial A_x}{\partial z} + \frac{\alpha}{2} A_x = +i\gamma \left(|A_x|^2 + \frac{2}{3} |A_y|^2 \right) A_x, \quad (2.6)$$

$$\frac{\partial A_y}{\partial z} + \frac{\alpha}{2} A_y = +i\gamma \left(|A_y|^2 + \frac{2}{3} |A_x|^2 \right) A_y. \quad (2.7)$$

A_x and A_y are the slowly varying envelopes for the two orthogonal directions, x and y . α and γ are the attenuation and nonlinear coefficient of fibers respectively. By solving these two equations, the phase difference is

$$\Delta\varphi = \varphi_x - \varphi_y = \frac{2}{3} \gamma L_{eff} (P_x - P_y) \quad (2.8)$$

where P_x and P_y are the powers in the two orthogonal directions and L_{eff} is the effective fiber length. If the incident laser is linearly polarized at an angle θ with the x direction, the Equation 2.8 can be written as:

$$\Delta\varphi = \frac{1}{3} \gamma L_{eff} P_0 \cos 2\theta \quad (2.9)$$

It is clear that the phase difference is decided by the launched power P_0 . For pulsed lasers, the instant power varies with time. As a result, the polarization state changes at different position of the waveform in time domain. This phenomenon is called the NPE.

2.2.2 Mode-locking enabled by NPE

Based on NPE effect, the polarization controller (PC) cooperating with the polarization analyzer works as an artificial SA. The process can be illustrated in Figure 2.3.

Figure 2.3 The schematic of pulse shortening based on NPE in a fiber laser cavity

The fibers act as the nonlinear medium to cause the NPE effect during the pulse propagating. As mentioned in chapter 2.2.1, the polarization states at different temporal positions within the pulse are varied. In this case, adjust the PC to force the polarization direction at the peak of the pulse to coincide with the direction of polarizer. The peak of pulse thus passes through the analyzer with minimum loss. On the other hand, the CW part and the wing of the pulse with lower intensity experience zero/small nonlinear phase shift, thus its polarization state is not rotated to coincide with the analyzer axis, experience a higher loss. Therefore, the pulses with high peak power are formed in the cavity. The speed of NPE is almost instantaneous and works as a fast SA, enabling the mode-locking in the femtosecond region.

2.3 Compact femtosecond TDF mode-locked laser in an all-fiber configuration

Based on the NPE mechanism, we demonstrate an all-fiber configuration based mode-locked TDF. The schematic of the experimental setup is shown in Figure 2.4. The active fiber is a 0.9 m TDF with 4 μm core diameter and 0.27 numerical aperture. It has 35 dB/m absorption at 1.57 μm . The WDM, PSISO and the output coupler OC were combined in a fibered hybrid device. The pigtail of the hybrid device is 0.85 m SMF with 8.2 μm core diameter and 0.14 NA. As both of the TDF and SMF (Corning, SMF-28) are of anomalous dispersion at 2 μm , a 1.3 m DCF (Nufern, UHNA7) with normal dispersion is added. The specifications of these fibers are listed in table 1. The dispersion values are calculated by commercial software, OptiFiber.

Figure 2.4 Schematic setup of the compact fiber oscillator

Table 2.1 Parameters of fibers used in the cavity

Fiber type	Core (μm)/NA	Dispersion at 1980 nm (ps^2/m)	Absorption (dB/m)	Length (m)
TDF	4/ 0.27	-0.036	~ 35	0.90
DCF	2.4/ 0.41	+0.046	N.A.	1.30
SMF28	8.2/ 0.14	-0.076	N.A.	0.85

Instead of using three individual components to realize the NPE based mode-locking, we use a hybrid OC-PSISO-WDM as a key component in this oscillator. The schematic diagram of the functional principle of this hybrid component is presented in Figure 2.5(a). The WDM (red) is reflection filter based, where 1570 nm reflected and 2000 nm transmit. The isolator (green) core is Faraday rotator based and sensitive to polarization. The optical coupler (blue) is a reflection based, outputting $\sim 10\%$ of the intra-cavity power, covering 1850 nm to 2100 nm. The transmission spectrum from signal to common (pump+signal) arm and the reflection spectrum of OC is shown in Figure 2.5(b), measured by a homemade amplified spontaneous emission (ASE) source. The hybrid component integrates the three functions in one and enables a simple way to obtain stable mode-locking and ultrafast pulse generation.

Figure 2.5 (a) Schematic of the hybrid component; (b) measured transmission spectrum of the hybrid component

By increasing the pump power to more than 400 mW and adjusting the PC, the mode-locking can be achieved. Once the mode-locking is confirmed, the mode-locking can be self-started when the pump power reaches 400 mW. But it operates typically at multi-pulse regime. To achieve stable single pulse operation, the pump power should be gradually decreased to 63 mW. This phenomenon refers to the pump power hysteresis [20]. For the NPE oscillator in soliton region, the mode-locking starts with a higher pump power. But there are multiple solitons formed in the cavity. After the mode-locking is acquired, the pump power can be decreased to reduce the number of solitons. As long as one soliton exists, the mode-locking is maintained [21].

At this situation, the output average power was 1 mW. For monitoring and measuring the laser performance, the following equipment was used: an optical spectrum analyzer (Yokogawa AQ6375L), an oscilloscope (Agilent DSO9254A, 2.5 GHz bandwidth) coupled with a 12 GHz InGaAs photo-detector (EOT, ET-5000F) and a high sensitivity thermal power meter (Ophir, 3A-FS).

The cavity length was 3.05 m, corresponding to 65.5 MHz repetition rates and 15.3 pJ pulse energy. The pulse train shows in Figure 2.6. Figure 2.7 is the spectrum of the oscillator. The central wavelength was 1980 nm with 16 nm 3 dB bandwidth.

Figure 2.6 Pulse train picked on oscilloscope

Figure 2.7 The optical spectrum of the output pulses

The net cavity dispersion was -0.038 ps^2 . Thus, the laser operated in the soliton region where the chirp induced by SPM and anomalous dispersion can compensate each other [19]. The side-lobe is the Kelly sideband [22] resulting in the interference between the dispersive wave [23] and the soliton. It is a typical spectrum of the mode-locking in soliton region.

This oscillator is further used as seed for the chirped pulse amplification system detailed in chapter 5.

2.4 All-anomalous-dispersion TDF mode-locked laser

2.4.1 Femtosecond laser with dispersion compensation free cavity

Like the oscillator mentioned in Chapter 2.3, DCFs are typically used in the cavity to control the total cavity dispersion. The DCFs in the 2 μm region were designed with high numerical aperture (NA) and small cores. The normal waveguide dispersion due to the high NA and small core size compensates the anomalous material dispersion. Based on this dispersion management technique, several leading works were demonstrated. The high energy (7.6 nJ) dissipative soliton was achieved in a NPE cavity, where DCF was used to shift the dispersion from anomalous to normal region. The output pulse was finally dechirped to 130 fs by a grating pair [24]. The impressive result of 58 fs pulses directly from an oscillator was demonstrated using a short TDF and DCF in a semiconductor saturable absorber mirror based mode-locked laser [25]. However, the huge mode field mismatch between the DCF and standard fiber significantly increases the splicing coupling loss. The smaller mode field (e. g. 11 μm^2 for ultra high numerical aperture (UHNA)) leads to a higher nonlinear coefficient, causing a higher nonlinear phase shifting along with the intended dispersion compensation. With excessive nonlinear phase, the pulse chirp can become non-monotonic, leading to optical wave-breaking and thus destabilization of the pulse propagation. It is why mode-locking started with multi-pulsing instead of stable single-pulsing operation in the previous reports [24, 26]. Such as the oscillator mentioned in Chapter 2.3, the DCF is used to compensate the cavity dispersion. The mode-locking starts with multiple solitons at higher pump power.

For the mode-locked TDF laser without dispersion compensation, the laser normally operates in the soliton regime. The minimum pulse duration is approximated by [27],

$$\tau \approx \sqrt{L \cdot |\beta_2|} \quad (2.10)$$

where, L is the fiber length, and β_2 is the group velocity dispersion.

To achieve ultrafast pulses by minimizing the total cavity dispersion, Yutaka Nomura proposed an alternative approach to replace the silica-hosted TDF with a ZBLAN-hosted TDF, which provided an ultra-low dispersion ($\beta_2 = 0.001 \text{ ps}^2/\text{m}$ at 2 μm) [28]. However, the ZBLAN fiber has a much lower melting temperature than silica fibers. Hence it is difficult to be compatible with the standard fiber devices, and bulk optics were inevitably used in the laser.

It is challenging to shrink the physical length using classical NPE-based fiber lasers, as it is limited by pigtailed fiber devices, including the polarizer, isolator, coupler and wavelength division multiplexer. In the previous reports, all-fiber TDF lasers without dispersion compensation conventionally produce mode-locked pulses with hundreds of femtoseconds (>500 fs) or picoseconds (ps) duration [29-31].

Here, we demonstrated a dispersion-compensation-free NPE mode-locked TDF laser. It mainly benefits from the hybrid fiber component mentioned in Chapter 2.3. The hybrid component could minimize the physical length of the fiber in the cavity to sub-1 meter and decrease the total dispersion for femtosecond pulse generation without dispersion compensation requirement [32].

The cavity structure is similar to the oscillator described in Chapter 2.3, except that it does not contain the DCF. The schematic setup of the experiment is shown in Figure 2.8. The all-fiber oscillator consists of a fiberized hybrid component (2.5 cm of physical length) with a 3-in-1 integrated functions, a segment of single mode TDF, and one fiber polarization controller. The whole cavity length is ~ 80 cm which consists of the 40 cm TDF and 40 cm pigtail fiber (Corning, SMF-28), corresponding to a repetition rate as high as ~ 250 MHz. The total dispersion of the cavity is calculated to be -0.045 ps², where the dispersion rate is -0.076 ps²/m of SMF-28 and -0.036 ps²/m of TDF at 1950 nm. Since all of the fibers used in the oscillator are of anomalous dispersion, the cavity will operate in the soliton regime. The pump source was made using a high power EDFA seeded by a C-band tunable laser, delivering up to 2 Watts of average power at 1560 nm. The pump laser is reflected by WDM port and launched into the cavity in the clockwise direction. The signal is then amplified by the TDF and 10 % of intra-cavity power is reflected as output by the output coupler. The PSISO ensures the unidirectional operation (clockwise) of the laser and applies the NPE mechanism together with the polarization controller.

Figure 2.8 Schematic setup of the dispersion compensation free fiber oscillator

The output state evolution and output power versus pump power are shown in Figure 2.9. The stable mode-locking operation self-started when the pump power increased to 575 mW with appropriate PC settings. Once mode-locking was triggered, the pump power could be applied from 380 mW to 692 mW without affecting the single-pulse fundamental frequency mode-locking of the oscillator, corresponding to an output average power of 18.4 mW to 36.3 mW and a slope efficiency of 5.7%. The residual pump at 1560 nm is negligible at the output port, and the power was verified to be less than 0.1 mW using a band-pass filter (Thorlabs, FB2000-500) and back calculations. Thus, the oscillator is stable in the mode-locking state even under fluctuating pump laser powers, substantiated by a stability test of 100-hour continuous operation at 575 mW pumping.

When the pump power increased beyond 720 mW, the mode-locking operation jumped from the fundamental frequency of 248 MHz to the second order harmonic of 496 MHz, via a short unstable transition state. To avoid device damage, the applied pump power was limited below 900 mW.

Figure 2.9 The output state evolution and output power versus pump power

The stable pulse trains of the two mode-locking states are summarized in Figure 2.10. The RF spectra are depicted in Figure 2.11 with a resolution of 10 kHz and a span of 0.75 MHz. The inset shows a broader spectrum with 10 MHz resolution over a span of 10 GHz. The fundamental repetition rate of pulses was 248 MHz and the SNR was >80 dB at fundamental frequency, confirming the stable, single-pulse mode-locking operation.

Figure 2.10 Pulse train of fundamental mode-locking (up) and harmonic mode-locking (below)

Figure 2.11 RF spectrum, 0.75 MHz span (the inset, 10 GHz span)

The output spectrum is shown in Figure 2.12(a), measured at a pump power of 580 mW. The central wavelength is 1950.0 nm and the 3-dB bandwidth is 18.2 nm. Tiny dips along the spectra ranging from 1900 nm to 1955 nm resulted from the O-H band absorption. The significant sidebands were resulted in the phase match coupling between dispersive radiation and the soliton. It well coincided with the all-anomalous cavity design. Given the contribution of Kelly sidebands (49.2%, calculated from the spectra integral) to the output power, the maximum pulse energy is ~ 74 pJ (146 pJ with Kelly sidebands, 36.3 mW in total average power), showing in Figure 2.12(b). The intra-cavity soliton energy can be calculated as 720 pJ (10% output ratio, 72 pJ), with a comparable value of theoretical soliton of 777 pJ for single mode fiber. There is no modulation in the central of the spectrum, which double confirms the single pulse operation without bonded pulses [33, 34].

Figure 2.12 Optical spectrum in (a) log scale and (b) linear scale.

Second-harmonic generation frequency resolved optical grating (SHG-FROG) was used to characterize the ultrafast pulses of the oscillator output. The pulse width was able to directly measure without amplification due to the ultrashort pulses and higher average output power (> 30 mW). It provides not only the pulse width by autocorrelation trace measurement, but also the phase information by time-frequency relation measurement. The measured and retrieved FROG traces with the error of 0.013 are shown in Figure 2.13(a) and 2.13 (b), respectively. The retrieved pulses with phase distribution in the time-domain and the frequency-domain are shown in Figure 2.13 (c) and 2.13 (d), respectively. The retrieved pulse width is 330 fs, and its corresponding time-bandwidth-product (TBP) of 0.47, which gives the Fourier transform

limited (FTL) pulse width of 220 fs and TBP of 0.315. The 220 fs FTL pulse width is close to 212 fs calculated by Equation 2.10. The phase distributions (dashed lines in Figure 2.13 (c) and 2.13 (d)) indicate the output pulse is slightly chirped, mainly attributed by the ~ 40 cm anomalous dispersive delivery fiber (SMF-28) at the output port.

Figure 2.13 (a) Measured FROG trace; (b) Retrieved FROG Trace; (c) and (d) Retrieved intensity (blue solid line) and phase (red dash line) in time-domain and frequency-domain

The oscillator would work in a mode-locking state with a long-term stability even under fluctuation of the pump laser, which was verified by a stability test of 100-hour continuous operation under a temperature controlled environment (19 degrees, Class 1000 clean room). Figure 2.14 shows the measured results with an average power of 34.6 mW and a standard deviation of 0.30 mW at the operation wavelength of 1940 nm. For the pulse-to-pulse stability, the periodic jitter can be extracted from the measured RF spectrum at the 10th order of harmonic frequency of 2.47984 GHz (Figure 2.11). Following D. von de Linde's model, the noise intensity is integrated over the frequency offset from ± 200 Hz to ± 10 MHz [35, 36]. The

periodic jitter of the output pulses is calculated as 174 fs, which is larger than expected. More accurate investigation on phase noise and jitter intends to be done in the future using an RF spectrum analyzer with phase noise measurement function, e.g., FSUP50.

Figure 2.14 The measured output power over 100 hours.

2.4.2 Broadly wavelength tunable mode-locking laser

In NPE based mode-locking oscillator, the Lyot filter effect exists [37]. Lyot filter is an artificial filter based on birefringence. When the light propagates in birefringent materials, the polarization components in the fast and slow axis have the phase delay. The phase delay depends on the wavelength. The cooperation of the birefringence and a polarizer induces the wavelength-dependent transmission.

The free spectral range (FSR) is determined by accumulated birefringence and central wavelength (λ), that is expressed as Equation 2.11. The transmission spectrum is formulated as Equation 2.12 and band-pass bandwidth of the full width at half maximum (FWHM) is approximated as $\text{FSR}/2$.

$$\text{FSR} = \lambda^2 / (\Delta n L). \quad (2.11)$$

$$T = \cos(\text{FSR} \cdot \pi / \lambda + \varphi). \quad (2.12)$$

where, birefringence $\Delta n = n_{\text{slow}} - n_{\text{fast}}$ is the difference of effective refractive index between the slow and fast axis of the fiber, and L is the fiber length. The phase is determined by the orientation of the PC. According to the Equation 2.11 and 2.12, the Lyot filter has a periodical

(sinusoidal) wavelength-dependent transmission. This periodical transmission provides an attained way for laser tuning.

By squeezing and rotating the PC in the cavity, the wavelength tuning of the laser could be achieved. The maximum tunable range of 143 nm from 1867 nm to 2010 nm of the central wavelengths was obtained. Continuous tuning over 100 nm (1890 nm to 1990 nm) was obtained just by rotating the PC without changing the squeezing strain. Figure 2.15 shows the output spectra with a spectral spacing of ~ 20 nm between the neighboring frames. The spectral profile maintained unchanged during the central wavelength tuning. The spectral width slightly varied ranging from 15.4 nm to 17.8 nm of FWHM. It supported transform limited pulse durations less than 275 fs under the assumption of sech^2 pulse profile.

Figure 2.15 The series of optical spectra with a ~ 20 nm spacing

The spectral width and the retrieved pulse widths over the whole tunable range with a sampling of ~ 10 nm were shown in Figure 2.16. The statistic pulse duration is 364 ± 17 fs (standard derivation, s.d.) and 3 dB spectral bandwidth is 16.4 ± 0.7 nm. The shortest and longest pulses were measured as 329 fs at 1900 nm and 392 fs at 1880 nm, respectively. Over the tunable

range, the laser typically yielded an average power of ~ 35 mW, but at the longer wavelength edge beyond 2000 nm it had a lower output power of ~ 32 mW due to a lower gain.

Figure 2.16 Pulse width and spectral bandwidth at the different operating wavelength.

In case of PM fibers or single mode fibers with a long distance are used in the cavities, it would result in a small band-pass bandwidth and a small FSR, e.g., 8.6 nm in [38] and 10 nm in [39]. One direct consequence is losing the capacity for femtosecond pulse generation in a lack of sufficient spectral bandwidth supporting, and this requirement gets more serious at 2000 nm compared with that at 1030 nm and 1550 nm. The other one is that multiple wavelengths may lase within the gain bandwidth, which prevents the continuous tuning over a broader wavelength range and single pulse operation. It will also affect the stability, but offer less practical value.

In our experiment, the FSR of the Lyot filter, formed by the single mode fiber of 0.8 meters, and we experimentally measured the FSR as 164 nm. A dual-wavelength CW lasing indicating the FSR, at 1842 nm and 2006 nm, was observed when the laser was operated below pump power of the mode-locking threshold. The effective birefringence of the fiber is calculated as 2.87×10^{-5} , which approximates well with the reported experimental birefringence of 3.17×10^{-5} and corresponding an FSR of 154 nm [40]. Figure 2.17(a) shows the measured spectrum (blue solid line) and the retrieved transmission spectrum of the Lyot filter (red dash line). The FSR of our fiber-based Lyot filter is more than 2 times as the earlier report using a birefringence plate [41]. Thus a larger continuous tunable range can be achieved. It should be noted that fused fiber devices (fused coupler/or fused WDM) are absent in our cavity. Fused

fiber devices based on mode-coupling mechanism typically have a narrow operation bandwidth, which probably reduces the tunable range.

The cutoff wavelengths of the tunable range are limited by two aspects, one is the lower transmission efficiency of the hybrid component at the short wavelength, and the other is the lower gain efficiency at the longer wavelength, respectively. Shown as blue curve in Figure 2.17(b), the efficiency gradually decreases from 1860 nm and has a hard-cut at 1820 nm, but keeps a high efficiency of >70% at longer wavelength extending to 2100 nm. The amplified spontaneous emission (ASE) spectrum of the thulium-doped fiber was plotted as red dash line in Figure 2.17(b). And the O-H bonds absorption lines were presented on the spectrum (1780 nm-1950 nm). The emission intensity is getting weaker above 2000 nm, which indicates lower gain efficiency at the longer wavelength.

Figure 2.17 (a) Experimental measurement of the FSR; (b) Transmission spectrum of the hybrid component and ASE of the thulium-doped fiber

To further extend the tunable range, a hybrid component with a shorter cutoff wavelength (e.g., 1700 nm) could be fabricated, for fully utilizing the emission wavelength range of TDF. Another simpler and feasible approach is to replace the thulium singly doped fiber by a thulium/holmium co-doped fiber (THDF). The THDF can provide an efficient gain from 1850 nm to 2200 nm because of the $^5I_8 - ^5I_7$ transition of Ho^{3+} , where our hybrid component works with high performance [42, 43].

2.5 Conclusion

In this chapter, we discussed the principle of the mode-locking laser and the NPE mechanism. Based on this, we demonstrated compact thulium-doped all fiber ring lasers. By compensating the cavity dispersion using DCF, the net cavity dispersion was controlled to -0.038 ps^2 . Benefiting from a hybrid OC-PSISO-WDM fiber device the all-anomalous dispersion laser cavity was also obtained. The cavity was minimized to 80 cm with a total dispersion of -0.045 ps^2 . The laser delivered 330 fs mode-locking pulses at a 248 MHz fundamental repetition rate. The novelty is the dispersion-compensation-free solution for a $2 \text{ }\mu\text{m}$ sub-500 fs compact oscillator design. The pulse duration can be further narrowed by applying shorter lengths of TDF with higher pumping absorption efficiencies. A GHz repetition rate of fundamental frequency mode locking could be expected in a fully gain fiber cavity design by removing the SMF. Moreover, the fiber-based Lyot filter enables the wavelength tuning. The tunable range is as large as 143 nm (1867 nm to 2010 nm). To the best of our knowledge, the achieved tuning range is the widest in femtosecond mode-locked TDFLs. This oscillator exhibits a high SNR and long-term stability. It may find applications in frequency metrology, arbitrary optical waveform generation, and seeding high average power ultrafast amplifier systems.

Chapter 3 Ultrafast pulse compression in an all-fiber configuration

In Chapter 2, we introduced the ultrafast mode-locked TDF oscillator based on NPE. However, the delivering pulses are in sub-nano-joule pulse energy level with hundreds femtosecond pulse width. Shorter pulses with medium-energy are needed for some applications such as broadband mid-IR generation, generating coherent supercontinua, and broadband coherent synthesis.

In order to achieve even higher pulse energy and shorter pulse width, the amplifier and compressor are needed. The pulse profile (both temporal and spectral) is affected by the dispersion and nonlinearity of the fibers. therefore, the management of the dispersion and nonlinearity is essential.

3.1 Pulse compression

3.1.1 Pulse compression by dispersion

For linear compression, the pulse compressed is achieved by dispersion. When an electromagnetic wave interacts with the bound electrons of a dielectric, the medium response, in general, depends on the optical frequency ω . This property, referred to as chromatic dispersion, manifests through the frequency dependence of the refractive index $n(\omega)$. The frequency-dependent refractive index results in frequency-dependent velocity when light propagates in materials. The dispersion can be mathematically explained by expanding the propagation constant β in a Taylor series.

$$\beta = n(\omega) \frac{\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \beta_2(\omega - \omega_0)^2 + \dots \quad (3.1)$$

where $\beta_m = \left(\frac{d^m \beta}{d\omega^m}\right)_{\omega=\omega_0}$ ($m = 0, 1, 2 \dots$).

β_1 is the inverse of the group velocity (speed at which the pulse envelope travels); β_2 is the group velocity dispersion (GVD) which describes the variation of group velocity for varying frequencies, and higher-order terms such as β_3 relate to higher-order phase change with respect to the frequencies. One can relate to the temporal broadening of a pulse comprised of multiple

frequencies, to be described by the term β_2 . β_2 may be positive ($\beta_2 > 0$; normal dispersion) or negative ($\beta_2 < 0$; anomalous dispersion). For normal dispersion materials, lower frequencies travel faster than higher frequencies, while the higher frequencies travel faster in the anomalous dispersion materials.

The pulse is said to have acquired a chirp due to this temporal delay difference between the different frequency components. Chirp refers to the instantaneous frequency changes with time. A chirp may be positive if the frequency increases with time or negative if the frequency decreases with time. Then, input pulses with positive chirp can be compressed by anomalous dispersion, while the opposite is true for pulses with negative chirp.

In fibers, the dispersion is not only determined by the material, but also related to the fiber geometry, namely the waveguide dispersion. It is the result of wavelength-dependence of the propagation constant of the optical waveguide. It is important in single-mode fibers. For longer wavelength, the fundamental mode spreads more from the core into the cladding. The cladding has smaller refractive index compared with core. This causes the fundamental mode propagates faster for the longer wavelength.

3.1.2 Pulse compression by nonlinearity

For nonlinear compression, the first step is to broaden the spectral width through nonlinear effects, typically SPM, as the shorter pulse width requires wider bandwidth. SPM refers to the self-induced phase shifting through pulse propagation in fibers. This is induced by optical Kerr effect. In nonlinear materials, the refractive index is not only frequency-dependent, but also intensity-dependent. It can be simply written in:

$$n(\omega) = n_0(\omega) + n_2 I \quad (3.2 \text{ a})$$

$$\Delta n = n_2 I \quad (3.2 \text{ b})$$

where $n_0(\omega)$ is the linear part, n_2 is the nonlinear refractive index and I is the optical intensity in the fiber. The change of the refractive index produces an instantaneous phase shift:

$$\varphi(t) = \omega t - \frac{2\pi}{\lambda} n L \quad (3.3 \text{ a})$$

$$\Delta\varphi(t) = -\frac{2\pi}{\lambda} \Delta n L \quad (3.3 \text{ b})$$

Then, the induced frequency shifts due to the phase shift is:

$$\Delta\omega(t) = \frac{d\Delta\varphi(t)}{dt} = -\frac{2\pi}{\lambda} n_2 L \frac{dI}{dt} \quad (3.4)$$

For pulsed lasers, the intensity is time-dependent. Hence, the induced frequency shifts are time-dependent as well. At the leading edge of a pulse ($t < 0$), the power increases with time ($\frac{dI}{dt} > 0$). Thus, the frequency red shifts ($\Delta\omega < 0$). On the contrary, at the trailing edge ($t > 0$), the frequency blue shifts ($\Delta\omega > 0$). The SPM always induces positive chirp.

This frequency shift would lead to the spectrum broadening or narrowing, depending on the chirp of the input pulse. For unchirped pulse, the SPM effect always leads to spectrum broadening, as new frequency is generated. The broadened spectrum often presents itself as an oscillatory structure with multiple peaks emanating from the central frequency, and the number of peaks is proportional to the nonlinear phase shift $\Delta\varphi(t)$.

The oscillatory structure of the spectrum stems from the time-dependence of the SPM-induced frequency chirp. There are two time points that give the same value of $\frac{dI}{dt}$ in general, which represents two waves with the same frequency referring to Equation 3.4. But these two waves have different phases due to the time difference. These two waves will interfere either constructively or destructively depending on their phase difference, leading to the multiple peaks in the spectrum.

For chirped input pulses, the sign of the chirp parameter plays a critical role to whether spectral broadening or narrowing will be observed. For positively-chirped input pulses, the low frequency component at the leading edge shifts to red and the high frequency component at the trailing edge shifts to blue. As a result, the spectrum is broadened. For negatively-chirped pulses, the SPM effect is inverse, and the spectrum is narrowed.

Hence, the input pulses need to be unchirped or positively-chirped during the nonlinear compression process. The SPM causes spectrum broadening and positive chirp which can be linearly compressed by dispersive elements. For 2 μm lasers that normally experience anomalous dispersion in standard fibers, the spectrum broadening and chirp compensating can happen simultaneously. Therefore, the nonlinear compression can be achieved in one stage.

3.2 Numerical simulation of pulse propagation in fibers

3.2.1 Pulse propagation in passive fibers

Pulse propagation in passive fibers can be described by NLSE. The generalized NLSE is then given by:

$$\frac{\partial A}{\partial z} = -\frac{\alpha A}{2} - \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial T^2} + \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial T^3} + i \left\{ \gamma |A|^2 A - \frac{2i}{\omega_0} \frac{\partial}{\partial T} (|A|^2 A) - T_R A \frac{\partial |A|^2}{\partial T} \right\} \quad (3.5)$$

where

$$T_R = \int_0^\infty t R(t) dt$$

$R(\tau)$ is the Raman response function. A is the envelope of the field moving at the group velocity (v_g); thus the real time, t , is related to T by $T = t - z/v_g$. The inverse group velocity is also known as first-order dispersion, which describes an overall time delay without affecting the pulse shape, $\beta_1 = 1/v_g$. α is the loss of the fiber. γ is the nonlinear coefficient and it is a function of the nonlinear refractive index n_2 and the effective cross-section area A_{eff} .

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (3.6)$$

The terms in the generalized NLSE above describe pulse phenomena as it propagates along the z -direction, and are tabulated in the table below.

Table 3.1 Physical phenomena of terms in generalized NLSE

Linear dispersion effects	
$\frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial T^2}$	Group velocity dispersion
$\frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial T^3}$	Third-order dispersion
Nonlinearity effects	
$\gamma A ^2 A$	Self-phase modulation
$\frac{2i}{\omega_0} \frac{\partial}{\partial T} (A ^2 A)$	Self-steepening
$T_R A \frac{\partial A ^2}{\partial T}$	Stimulated Raman scattering

3.2.2 Pulse propagation in active fibers

In active fibers, the pulse is amplified. The gain and the nonlinearity interacts with each other. So, the gain effect must be considered. The pulse propagation in active fibers is governed by the Ginzburg-Landau Equation (GLE) shown below [19]:

$$\frac{\partial A}{\partial z} = \frac{(g(z, \omega) - \alpha)}{2} A - \left(\frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial T^3} + ig(z, \omega) T_2^2 \right) A + i\gamma(1 + \frac{i}{\omega_0} \frac{\partial}{\partial T}) A \int_{-\infty}^{\infty} R(\tau) |A(z, T - \tau)|^2 d\tau \quad (3.7)$$

All the parameters' definitions are the same as in Equation 3.5. T_2 refers to the dipole relaxation time. The value of gain, $g(z, \omega)$, is dependent on both of fiber length and frequency.

For the active fiber, the profile of gain $g(z, \omega)$ is obtained by calculating the rate equation in the propagation direction [44]. Compared with conventional gain medium (YDF or EDF), the rate equation of thulium doped gain medium is four-level and involves cross-relaxation (CR) effect when pumped by 793 nm laser. CR is a process that can help to increase quantum efficiency. The energy band of thulium ions is shown in Figure 3.1(a) [45] and the common absorption and emission spectra is shown in Figure 3.1(b). When pumped by 793 nm, atoms can jump to 3H_4 . Partial of atoms in this level can drop to 3F_4 directly. The energies released through this process can be reabsorbed by the ground-state atoms. Thus, there is a possibility that absorption of one pumping photon can release two signal photons at the range of 1700-2100 nm. So, the quantum efficiency can be larger than 100%.

Figure 3.1 (a) Energy band of thulium ions and cross relaxation process, (b) the absorption (blue curve) and emission (red curve) cross section spectra of thulium ions

The general rate equations at any point along the length of the fiber can be expressed as below:

$$\frac{dN_0}{dt} = -(W_{01} + W_{03})N_0 + W_{10}N_1 - CR + N_1\Gamma_1 + A_{10}N_1 + A_{30}N_3 \quad (3.8)$$

$$\frac{dN_1}{dt} = W_{01}N_0 - W_{10}N_1 + 2CR + N_3\Gamma_3 + A_{31}N_3 - (\Gamma_1 + A_{10})N_1 \quad (3.9)$$

$$\frac{dN_3}{dt} = W_{03} - CR - (A_{30} + A_{31} + \Gamma_3)N_3 \quad (3.10)$$

$$N_{total} = N_0 + N_1 + N_3 \quad (3.11)$$

$$CR = k_{3101}N_3N_0 - k_{1310}N_1^2 \quad (3.12)$$

where W_{ij} is the pump absorption rate given by:

$$W_{03} = \frac{\lambda_p \sigma_{ap}}{hcA} (P_f + P_r) \kappa_p \quad (3.13)$$

$$W_{01} = \frac{\lambda_s \sigma_{as}}{hcA} (S_f + S_r) \kappa_s \quad (3.14)$$

$$W_{10} = \frac{\lambda_s \sigma_{es}}{hcA} (S_f + S_r) \kappa_s \quad (3.15)$$

$$\frac{dP_{f,r}}{dz} = \mp P_{f,r} [\kappa_p (\sigma_{ap} N_0 - \sigma_{ep} N_1) + \delta_p] \quad (3.16)$$

$$\frac{dS_{f,r}}{dz} = \pm S_{f,r} [(\sigma_{es} N_1 - \sigma_{as} N_0) + \delta_s] \quad (3.17)$$

The positive sign relates to the forward (backward) direction of the signal (pump), and the negative sign is for backward (forward) direction of the signal (pump). The physical meaning of all symbols used in these equations are listed in Table 3.2. i, j, m and n are integral number from 0 to 3. The energy levels 0 to 3 represent $^3H^6$, $^3F^4$, $^3H^5$ and $^3H^4$ of thulium ions.

Table 3.2 The physical meaning of the symbols used in Equations 3.8-3.17

Symbol	Physical meaning
A_{ij}	Spontaneous transition rates
$\sigma_{ap}, \sigma_{ep}, \sigma_{as}, \sigma_{es}$	Absorption/emission cross section of the pump/signal
P_f, P_r, S_f, S_r	Forward and backward propagating pump and signal power
N_i	Number density of the active ions
Γ_i	Nonradiative transition rates
κ_s, κ_p	Overlapping factor between the signal/pump and the fiber doped area
k_{ijmn}	Energy transfer processes i to j and m to n
A	Doped area of the fiber
δ_s, δ_p	Intrinsic attenuation of the signal/pump in the fiber

3.3 Generation of 65-fs pulses by dispersion and nonlinearity management

Recently, significant progress has been made in the development of sub-100 fs fiber lasers at 2 μm [28, 46-51]. The first sub-100 fs pulses were reported in 2012 [11]. The authors demonstrated 58 fs pulses in a semiconductor saturable absorber mode-locked fiber laser with an extremely short cavity for the first time. The state-of-the-art shortest pulse width at 2 μm is 13 fs. The performance was achieved by the combination of a rod-fiber based chirped pulse amplification laser system and a gas-filled hollow core fiber based nonlinear compressor [52].

In those above lasers, bulk optics have been adopted either inside or outside of the laser cavity for mode-locking or pulse compression. For all-fiber configurations, the shortest pulse at 2 μm was demonstrated by Herda et. al [51]. In their system, amplified 1.56 μm femtosecond pulses shifted the lasing wavelength to 1.95 μm via soliton self-frequency shift in highly nonlinear fiber (HNLF), working as a 2 μm ‘seed’. After the thulium-doped fiber amplifiers and triple-stage solitonic compression, pulse duration as short as 27 fs was achieved. This laser system is relatively complicated including multistage amplifiers and nonlinear compressors. Moreover, the frequency shifting requires accurate laser power control for desired operating wavelength of the seed and the fiber compressor need to be critically controlled in millimeter scale.

Through nonlinear compression in a dispersion and nonlinearity managed fiber chain, we generated 65 fs pulses delivered from a compact ultrafast thulium-doped all-fiber laser.

3.3.1 Experimental setup and results

The schematic design of the laser is shown in Figure 3.2. The laser includes a compact fiber oscillator, a normal dispersive fiber stretcher, a double-clad TDF (DC-TDF) amplifier and a nonlinear compressor.

Figure 3.2 The schematic diagram of the laser setup. (DC-)TDF: (double-clad) thulium-doped fiber; PC: polarization controller; DCF: dispersion compensation fiber; ISO: fiber isolator; HNLF: highly nonlinear fiber. The output fiber is angle cleaved with 8 degrees.

A dispersion-managed mode-locked oscillator (different with the oscillator described in Chapter 2) serves as the ‘seed’ which outputs 50 pJ pulses with 41.5 nm spectral bandwidth. At 2 μm , dispersion management gets more challenging, since the dispersion, either normal or anomalous, of the commercial fibers is much larger ($>40 \text{ fs}^2/\text{mm}$) compared with the dispersion

value at 1 μm or 1.5 μm . With the hybrid device, the physical length of the cavity can be shortened. Therefore, the net cavity dispersion can be well controlled within a smaller absolute error and the accurate dispersion management can be more easily handled. Furthermore, the normal dispersion fibers at 2 μm usually have smaller cores ($\sim 3 \mu\text{m}$ of the diameter) and higher nonlinearity. Shorter fiber can prevent instability and multi-pulsing caused by overdriven nonlinearity. In the experiment, the cavity length is only $\sim 115 \text{ cm}$ including 45 cm single-clad TDF (second-order dispersion: $-40 \text{ fs}^2/\text{mm}$), 40 cm DCF (Nufern UNHA4, dispersion: $+93 \text{ fs}^2/\text{mm}$) and 30 cm single mode pigtail fiber (SMF28, $-76 \text{ fs}^2/\text{mm}$). The net cavity dispersion is about -8000 fs^2 . Thus the NPE based mode-locked oscillator will operate in the dispersion managed soliton regime.

The oscillator is pumped by a single-mode erbium-doped fiber laser at 1565 nm, where the TDF (core diameter 4.2 μm , N.A. 0.27) has an absorption rate of 35 dB/m. The mode-locked oscillator can self-start with 400 mW pump power in the multi-pulse regime, and converge to the stable single-pulse mode-locking state by reducing the pump power to 140 mW. The average output power is $\sim 9 \text{ mW}$ and pulse energy is 50 pJ, which is insufficient for pulse characterization by our autocorrelation measurement tool. The oscillator operates at the central wavelength of 1980 nm, and 3 dB spectral width is measured as 41.5 nm by an optical spectrum analyzer (OSA, Yokogawa AQ6375L), shown in Figure 3.3. It corresponds to a transform-limited pulse duration of 100 fs (Sech^2 pulses). The spectral sidebands are efficiently suppressed by $>10 \text{ dB}$ respect to the central wavelength.

Figure 3.3 Mode-locked fiber oscillator output optical spectrum (0.2 nm resolution).

For tens of femtosecond pulse generation, it requires an even larger spectral bandwidth (~ 100 nm) and optimal dechirping. It is challenging to achieve such a broad spectrum directly from a fiber oscillator even with an ideal dispersion management. Nonlinear compression in fibers provides a promising approach to obtain >100 nm spectral bandwidth and generates tens of femtoseconds pulses.

Due to the anomalous dispersion, pulses from the oscillator are negatively-chirped. The negative chirp would cause spectrum narrowing in the consecutive amplifier. In order to prevent from the narrowing, a 6-m long DCF is spliced to the output pigtail (0.6 m SMF) of the oscillator to stretch the pulses. The pulses are stretched to ~ 10 ps after the DCF with 0.56 ps² group delay dispersion (GDD).

A DC-TDF based power amplifier is built to boost the average power and pulse energy. A 3.3-m DC-TDF (Nufern, SM-TDF-10P/130-HE, -86 fs²/mm) is pumped by a 6-W 793-nm laser diode (BWT, K793DA3RN-6W) through a fiber pump/signal combiner. A section of 26 cm single mode fiber (Corning, SMF-28) was used after DC-TDF to strip the residual pump. The spectrum gets symmetrical broadening during the amplification process due to the SPM effect. The measured spectra at different output power levels are shown in Figure 3.4(a). At the same time, the pulse width is narrowed during the amplification process. Figure 3.4(b) shows the pulse width at different output power level. The consequent temporal compression can be understood as the interplay between SPM and anomalous dispersion. The positive chirp induced by SPM can compensate the negative chirp induced by the anomalous dispersion. Unlike dispersion effect, SPM effect is power dependent. Therefore, the compression factor changes with power for a fixed fiber length. The shortest pulse width was 126 fs at 1100 mW output power. When the output power was further increased, the pulse width was also increased due to the over-compensated positive chirp.

Figure 3.4 (a) The measured spectra at different output power levels; (b) the pulse width at different output power level.

After the amplifier, pulses are delivered to a short piece of HNLF (24 cm). The HNLF has a mode-field-area of $\sim 11 \mu\text{m}^2$ corresponding to a nonlinear coefficient of $8.7 \text{ W}^{-1}\text{km}^{-1}$, and the dispersion is about $60 \text{ fs}^2/\text{mm}$. A 26 cm anomalous dispersive SMF is used to compensate the normal dispersion and SPM induced positive chirp in HNLF. The length of HNLF and SMF is optimized by a 1 cm interval with the feedback of final output. The final broadened spectra and pulse width change with power are presented in Figure 3.5. Because of the mode-field-diameter mismatching between the SMF and HNLF, there is 1.5 dB splicing loss.

Figure 3.5 Final pulse width changes with power

The shortest final pulse width was 62 fs at 610 mW power, however the parasitic lasing would happen occasionally when the laser operated at a higher power than 560 mW. The parasitic lasing is the unwanted laser operation in the amplifier. Due to the mismatched effective mode area between the TDF and the HNLF, the Fresnel reflection at the splicing point cannot be avoid. The light reflected at the splicing point may oscillating in the amplifier. The parasitic lasing would not only extract the energy, but also have the risk of components damage. So, the output power limited to 560 mW with 65 fs pulse width.

At 560 mW output power level, the broadened spectra in the amplifier and the HNLF at this power level compared with the original spectrum are shown in Figure 3.6. In the TDF, the spectrum got broadening to FWHM of 62 nm (plotted as blue dashed curve in Figure 3.6). The pulse was compressed to ~ 160 fs simultaneously due to the nonlinear compression. The average power and pulse energy from amplifier are 800 mW and 4.5 nJ, corresponding to 25-kW peak power. The high peak power enabled the further spectrum broadened to more than 160 nm (at -6 dB level) in the HNLF (shown in a red dashed curve in Figure 3.6). The symmetrical broadened spectra and the modulations indicate that the broadening is induced by SPM. The clipped spectrum at the shorter wavelength (1900 nm) is due to the limitation of the OSA (1900-3400 nm).

Figure 3.6 Spectrum broadening in fiber amplifier and HNLF. Spectrum measured after the amplifier (blue dashed) and final output (red solid), respectively. The output spectrum from oscillator is indicated as a reference in black dotted line.

The time-frequency properties of the output power are characterized using FROG (Mesaphotonics, 0.5 mm BBO crystal for second harmonic generation). Figure 3.7(a) and (b) show the measured and retrieved FROG traces. Figure 3.7(c) shows the retrieved pulse profile of 65 fs, and it exhibits several small side lobes, but the main pulse takes 84% of the total energy. The small side lobes in time domain is due to the nonlinear phase shift induce by SPM. And the nonlinear phase shift cannot be compensated by dispersion. The retrieved spectrum (blue) and phase (orange) are shown in Figure 3.7(d). The asymmetrical side-lobes of the pulse and the cubic phase of the spectrum reveal the residual higher order dispersion referring to β_3 in Equation 3.5 and 3.7. We mainly attribute it to the third order dispersion (TOD), since most of the fibers (except HNLF) in the fiber chain have a positive third-order-dispersion.

Figure 3.7 Pulse characterization by FROG. (a) measured FROG trace, (b) retrieved FROG trace, (c) retrieved pulse profile (d) retrieved spectrum (blue) and phase (orange dot), and a comparison spectrum measured by OSA (black dash).

3.3.2 Numerical simulation of pulse evolution in fiber chain

To understand the ultrafast pulse formation in the fiber chain, the pulse evolution is numerically simulated with NLSE and GLE for passive and active fiber respectively. The simulation for passive fibers based on NLSE, is well developed [53]. For active fibers, the pulse propagation interweaving with gain effect makes the simulation too complicate. In order to simply the simulation, the profile of gain $g(z, \omega)$ was simulated independently. In the z direction along the fiber, $g(z, \omega_0)$ is obtained by calculating the rate equations (in central wavelength ω_0) described in Chapter 3.2.2; in the frequency domain, $g(z, \omega)$ was fitted by the emission spectrum of thulium ions [18].

In the simulation, the input is the electric field of a transform-limited pulse with the same spectrum of the oscillator output. As the oscillator operates in soliton region, the input for the simulation was assumed in sech^2 shape. The pulse propagates through the seven fiber sections, SMF-NDF-SMF-(DC-TDF)-SMF-HNLF-SMF, with alternating anomalous and normal dispersion. The dispersion (at 1980 nm) map of the fiber chain is shown in Figure 3.8, where the second order and third order dispersion are indicated in blue and red curves, respectively.

Figure 3.8 dispersion map of the fiber chain. Different fiber types are denoted with different color

The value of main parameters (at central wavelength 1980 nm) used in the simulation are listed in Table 3.3.

Table 3.3 The value of the parameters used in the simulation

	SMF	DCF	DC-TDF	HNLF
β_2 (fs^2/mm)	-76	93	-86	60
β_3 (fs^3/mm)[54]	104	154	96	-33
γ ($m^{-1}kW^{-1}$)	1.2	4.7	1.1	8.7

The evolution of the spectral and temporal profile along the fiber chain is shown as Figure 3.9 (a) and (b), where logarithmic scale is adopted covering the large dynamic range of the power amplification in DC-TDF. The power distribution along the DC-TDF is obtained by calculation from rate equations. And the evolution at the last three short sections is zoomed in as Figure 3.10 (a) and (b) in linear-scale. The spectrum starts gradually broadening afterward DC-TDF due to the pulse energy amplification and pulse duration compression simultaneously. The 3 dB spectral bandwidth increases to 63 nm after DC-TDF and SMF, 89 nm after HNLF and 93 nm at the final output. The symmetrical multiple-peak spectral profile reveals the self-phase modulation dominated nonlinear process.

Figure 3.9 Full range spectral and temporal evolution along the fiber chain (logarithmical scale is chosen to cover the large dynamic range in the amplifier, color bar unit: dB)

Figure 3.10 Zoomed-in evolution at the last three sections of fibers (linear).

The pulse duration varies along the fiber chain with a strong temporal breathing ratio of 165. The maximum pulse duration is observed as 10.26 ps at the end of NDF (stretcher), and shortest duration of 62 fs at final output. Figure 3.11 shows the final output of the experiment (blue) and the simulation (red). It is noticed that there is a slight discrepancy between simulation and experiment. The asymmetrical shape of the experimental results is possible due to the higher order dispersion (fourth and fifth).

Figure 3.11 The final output temporal profiles of the experiment (blue) and the simulation (red)

As shown in Figure 3.10 (a) and (b), the short piece HNLF enables the effective spectrum broadening, but due to its large normal dispersion, the pulse spreads simultaneously. That lowers the peak power of the pulse and saturates spectrum broadening. Thus, targeting even shorter pulses, a HNLF with lower dispersion should be designed and adopted to extend the spectral bandwidth further. As well, negative third-order dispersion fibers should be used to suppress the side lobes of the dechirped pulses. Moreover, oscillator and amplifier based on polarization-maintaining fiber intend to be adopted to improve the stability further.

3.4 Conclusion

We have achieved 65 fs pulses in a compact thulium-doped all-fiber laser. The ultrafast pulse benefitted from the ultra-compact mode-locked fiber oscillator and the dispersion-nonlinearity managed fiber chain. The passive and active fiber chain effectively broadened the spectrum and compressed the pulses. Numerical simulation based on the split-step Fourier method was carried out to investigate the formation and evolution of the ultrafast pulses. Such all-fiber-based sources have significant advantage over bulk or fiber/bulk hybrid sources for many practical applications, such as remote sensing, medical surgery, high-precision spectroscopy, thanks to their excellent robustness, portability and compactness

A shorter pulse duration, even few-cycles is expected when the proper HNLF fibers is designed and adopted. From Figure 3.10, the pulse is stretched due to dispersion of HNLF. And the spectrum broadening is not obvious in the end, as the peak power is reduced. The HNLF with lower dispersion value is expected to keep the peak power and broaden the spectrum further.

Chapter 4 Mid-IR frequency generation pumped by ultrafast TDF laser

For the rare-earth doped silica-hosted fiber, the laser wavelength was limited by the emission cross section of the rare-earth ions. The longest wavelength achieved for ultrafast laser was $2.14\text{ }\mu\text{m}$ [55]. Even for CW lasers, the longest wavelength obtained was $2.21\text{ }\mu\text{m}$ with 130 mW average power [56]. However, the ultrafast laser beyond $2.2\text{ }\mu\text{m}$ are in great demands for many applications, such as pumping nonlinear interactions, spectroscopy and gas detection. Generation of the ultrafast laser emission beyond $2\text{ }\mu\text{m}$ could also be applied in micro-surgery due to the strong absorption and low scattering in bio-tissues [57-59].

For some applications including optical frequency metrology [60], precision spectroscopy [61], optical coherent tomography [62] and remote sensing [63], they require laser source with broad bandwidth. Moving into the mid-infrared (mid-IR), for wavelengths beyond $2\text{ }\mu\text{m}$, pushes the applications further in LIDAR [64], hyperspectral imaging [65], medical and biological system [66].

The ultrafast TDF laser is a great candidate to generate mid-IR sources with ultrashort pulse width or broad bandwidth. Compared with YDF and EDF laser, pumping at longer wavelengths is more favorable for efficient mid-IR sources generation.

4.1 The nonlinearities that induce frequency shift

The new frequency generation is as a result of the nonlinearity. In fiber optics, nonlinear refraction and inelastic scattering are two reasons for the nonlinear effects. Nonlinear refraction refers to the intensity-dependent refractive index which responds to Kerr effect; stimulated inelastic scattering corresponds to the optical field transfers part of its energy to the nonlinear medium. In this chapter, we focus on the nonlinear phenomena including Raman scattering, soliton fission and dispersive wave generation.

4.1.1 Stimulated Raman scattering

Stimulated Raman scattering (SRS) belongs to inelastic scattering. The incident photons are scattered by interacting with the molecules. A fraction of these scattered photons transfer parts of their energy to the medium and convert to lower frequency photons, called Stokes wave. The transferred energy, known as phonons, are determined by the molecular bindings. For silica fibers, the Raman effect induces a gain whose peak locates in down-shifted 13.2 THz [67]. Thus, the peak frequency of Stoke wave generated in silica fiber is

$$f_s \cong f_0 - 13.2 \text{ THz} \quad (4.1)$$

When the input pulse is ultrafast (pulse width $< 1\text{ ps}$), the spectrum is wide enough. The shorter wavelength (higher frequency components) can work as pump to transfer energy to longer wavelength of the same pulse through Raman effect. So that there is a continuous transfer of energy from the shortest to the longest wavelengths within the spectrum. As a result, the spectrum shifts to longer wavelength as the pulse propagating. This phenomenon is called intra-pulse Raman scattering.

4.1.2 Soliton fission

The chirps induced by SPM and anomalous dispersion are in opposite sign. In a certain condition, these two chirps can cancel out each other. As a result, pulses can propagate in fibers without any distortion in both time-domain and frequency-domain under the balance of anomalous dispersion and SPM. Such kind of pulses are called solitons. This undistorted situation can exist only when the input pulse has the sech^2 temporal shape and the soliton order

$$N = \sqrt{\frac{\gamma P T^2}{|\beta_2|}} = 1 \quad (4.2)$$

where, γ is the nonlinear coefficient and β_2 is dispersion of the fiber. P and T are the peak power and pulse width of incident pulses respectively.

For higher value of N ($N > 1$), the pulse called higher order soliton experiences a periodic evolution. The pulses will narrow, split and recombine with a period of $\frac{\pi T^2}{2|\beta_2|}$.

In fact, pulse propagation in optical fiber is not only influenced by dispersion and SPM, but also other high-order effect, such as higher-order dispersion and Raman scattering. When $N > 1$, these effects act as perturbations, causing the fission of higher order solitons into the constituent fundamental solitons [19]. The fission solitons have wider spectral width and shorter pulse width compared with the original pulse.

Normally, the fission soliton experiences obvious intra-pulse Raman scattering. Considering the Raman gain spectrum of silica, pulses with wider spectrum would have larger gain for the intra-pulse Raman scattering effect if the spectral width is below 13.2 THz (corresponding to ~ 176 nm at $2 \mu\text{m}$). In addition, the frequency shift induced by intra-pulse Raman scattering is inversely proportional to the fourth power of the pulse width [19]. Thus, normally, the frequency shift would happen after the soliton fission. This combination process of soliton fission and intra-pulse Raman scattering is called the soliton self-frequency shift (SSFS). And the pulses generated through this process are called Raman solitons. As the soliton red-shifts to longer wavelengths, the Raman shift will be weakened due to the combination of increased dispersion, energy loss due to material absorption and reduced nonlinearity. The red-shift of the soliton will gradually stop.

4.1.3 Dispersive wave

During the soliton fission process, the presence of higher order dispersion can lead to the transfer of energy from the soliton to the phase matched non-soliton radiation which is in the normal dispersion region. This non-soliton radiation is called dispersive wave (DW). The frequency of DW is controlled by the general phase-matching condition requiring that DW propagate with the same phase velocity as that of the soliton. The frequency difference between dispersive wave and soliton wave can be approximately described as:

$$\Omega_d \approx -\frac{3\beta_2}{\beta_3} + \frac{\gamma P \beta_3}{3\beta_2^2} \quad (4.3)$$

4.2 Highly efficient tunable Raman soliton by optimized chirp at $2 \mu\text{m}$

We present an efficient wavelength tunable Raman soliton laser system through the process of SSFS. It provides widely and continuously tunable spectral range and high quality femtosecond temporal performance.

Fiber laser cavity configurations based on nonlinear polarization evolution (described in Chapter 2) and nonlinear amplifying loop mirror [68] enable artificial filter effect for wavelength tuning for rare-earth doped fiber oscillators. The tunable range achieved was mainly limited by the emission spectra of doped ions.

Recently, Raman soliton lasers with large tunable spectral range have been investigated by several research groups. In the standard silica fibers, the longest wavelength is reported by M. Yu. Koptev [69]. They reported a thulium/ytterbium co-doped silica fiber amplifier operating in the Raman soliton regime with the spectral tunability from 2 μm to near 2.3 μm . The conversion efficiency achieved, referring to the ratio of the Raman soliton energy to the total output energy, was around 40%. J. Jiang also demonstrated Raman soliton generation in TDF amplifier from 1.9 to 2.2 μm with an efficiency of $\sim 50\%$ [70]. Extending to even longer wavelength in microstructured tellurite fibers, M.Y. Koptev achieved spectral coverage up to 2.65 μm [71] based on a cascade SSFS setup. According to their results, the efficiencies were typically smaller than 50%. S. Duval obtained watt-level laser sources tuning from 2.8 – 3.6 μm in an erbium doped fluoride fiber amplifier seeding by 440 fs pulses at 2.8 μm with the efficiency ranging from 45% to $\sim 70\%$ [72]. Y. Tang used a two-stage SSFS setup to generate 100 fs Raman solitons tunable from 2 to 4.3 μm in fluoride fiber [73]. 35% energy was transferred to Raman solitons, even by ignoring the coupling efficiency. Among these research results, the conversion efficiency reported was capped at $\sim 70\%$.

In order to improve the efficiency, we proposed to optimize the chirp of the input pulse by adding DCF. The optimized DCF length was based on the GLE simulation. A Raman soliton laser with high conversion efficiency up to 97% is demonstrated in a compact all-fiber setup. The laser has the wavelength tunability from 1.98 to 2.31 μm with sub-200 fs pulse width. Over the whole wavelength range, the efficiency is from 76% to 97%.

4.2.1 Experimental setup and results

The schematic of the experimental setup is shown in Figure 4.1. The oscillator was a mode-locked fiber laser based on NPE mechanism described in Chapter 2.3. Pulses from the oscillator was pre-chirped by a 5.7 m DCF. The compensation fiber length was optimized according to the dispersion calculation. Simultaneously, the chirp value of input pulses was adjusted by the DCF. After the pre-compensation, Pulses are amplified and shifted to longer wavelength through SSFS in a 3.3 m TDF amplifier which is pumped by 793 nm laser diode (LD).

Figure 4.1 The schematic of experiment setup for tunable Raman solitons generation in an all-fiber one-stage TDF amplifier

The output spectra were measured by the OSA. By varying the 793 nm LD (DILAS, 32W) pump power, Raman solitons with wavelength shifting from 1.98 to 2.31 μm were achieved. Figure 4.2 shows the evolution of the output spectra with the increase of the LD power (P). The launched pump power at each spectrum lists on the right of the figure. The corresponding pulse energy (E) of Raman soliton was calculated based on the output spectra. The central wavelength of the Raman soliton simultaneously shifted to the longer wavelength as the LD power increased during the amplification process. It reached the longest central wavelength of 2.31 μm with the total output power of 650 mW under 5.8 W pump power. By further increasing the pump power, the second Raman soliton would appear. However, no significant red-shift of the first soliton was observed.

Figure 4.2 The measured output spectra as a function of LD pump power; P: the launched pump power; E: the corresponding Raman soliton pulse energy

In both passive and Tm-doped silica fibers with single soliton generation, 2.31 μm is the longest wavelength obtained so far. Stretching to silica cut-off is benefited from the high conversion efficiency, i.e., most of the energy was transferred to Raman solitons. So the SSFS process which is proportional to the peak intensity was enhanced. Moreover, the remaining energy of initial pulses was in sub-nJ when the Raman soliton was formed. They could not experience enough gain to form a second order soliton when the first one reached at 2.31 μm .

By further increasing the pump power, we can observe further red shift of the central wavelength. However, the second Raman soliton would appear. The spectrum at 700 mW output power shows in Figure 4.3 with purple colour. At this power level, the central wavelength only increased by 4 nm, but the pulse energy decreased to 7.51 nJ even the total average power increased. The green, blue and orange are the measured spectra at power of 900 mW, 930 mW and 950 mW respectively. No obvious red-shift of the first Raman soliton was observed anymore; only the second Raman soliton shifts. The central wavelength and pulse energy of the Raman soliton changing with the output power is shown in Figure 4.4. After 2300 nm, the pulse energy decreases with the power.

Figure 4.3 The spectra with two formed Raman solitons; Purple: 700 mW; Green: 900 mW; Blue: 930 mW; Orange: 950 mW

Figure 4.4 Pulse energy and central wavelength of the Raman soliton change with output power.

In order to investigate the temporal profile of Raman solitons, we used FROG to characterize the Raman soliton pulses. Figure 4.5 shows the measured pulse width of Raman soliton at different output wavelength. The shortest pulse width was 150 fs at the central wavelength of 2030 nm. Pulse durations increased slightly as shifting to longer wavelengths. This could be caused by the larger dispersion the Raman soliton encountered at longer wavelengths.

Figure 4.5 The measured pulse width of Raman soliton versus the output wavelength.

At the wavelength of $2.31\ \mu\text{m}$, the measured pulse width was 186 fs. The retrieved pulses in the time-domain and the frequency-domain are shown in Figure 4.6(a) and 4.6(b), respectively. The measured and retrieved FROG traces with the error of 0.0056 are shown in Figure 4.6 (c) and 4.6(d), respectively. The FROG results verified that the Raman soliton pulses maintained clean without any pedestal even at the longest wavelength.

Figure 4.6 The FROG measurement results of the Raman soliton at 2.31 μm , retrieved intensity and phase in time-domain (a) and frequency-domain (b); (c) Measured FROG trace; (d) Retrieved FROG trace

The conversion efficiency to Raman soliton was measured at different wavelength and the results are shown in Figure 4.7. The highest conversion efficiency 97% was achieved at 2.03 μm . The value remained above 90% before 2.22 μm , and decreased to 76% at 2.31 μm . The efficiency reduction in longer wavelengths was due to the gain spectrum of TDF and background loss of silica. The emission spectrum of thulium ions cuts off around 2.2 μm [74], so the Raman soliton with wavelength larger than 2.2 μm would not be amplified. Furthermore, after 2.2 μm , the background loss of silica (black curve in Figure 4.7) increased dramatically [75]. Even though the efficiency decreased in longer wavelength regime, the efficiency across the tunable range is $>76\%$, which is higher than those reported in previous works [69-73].

As the lower efficiency at longer wavelength was limited by the background loss of silica fiber, we calculated the efficiency by neglecting the background loss. The orange-colour crosses in Figure 4.7 show the calculated efficiency beyond 2.2 μm . It is worth to note that the lowest efficiency was raised to 82%. By replacing the standard silica fiber with IR silica or fluoride glass fiber, more than 80% efficiency over the whole range would be achieved providing low loss splicing between silica fiber and fluoride fiber.

Figure 4.7 The measured efficiency of Raman solitons with and without background loss of silica

4.2.2 Numerical simulation of Raman soliton generation in TDF

During the Raman soliton process in fibers, the energy transformed from the original pulse to the Raman solitons can be calculated according to the eigenvalues that describe energy of solitons [76], if the input pulses are transform-limited and propagates in the passive fibers. However, in the case of chirped input pulses propagating in active fibers with optical gain, the assumption is not valid anymore [77]. In order to investigate how the chirp value of input pulses influence the conversion efficiency, numerical simulations based on GLE were performed.

The numerical results were simulated by launching 7.7 pJ (corresponding to 0.5 mW average power from the oscillator) pulses with 15 nm spectral width at 1.98 μm to 3.3 m TDF. The pulse width was changed by setting different chirp values. The pulses directly delivered from the oscillator was assumed as transform-limited, and the peak power was smaller than 30 W. Hence, the nonlinear effects in the passive fibers can be ignored. The chirp value was calculated by the considering the total dispersion provided by DCF (β_2 dispersion: $\sim 60 \text{ ps}^2/\text{km}$). Thus, the relationship between chirp value and the length of DCF is linear.

The conversion efficiency to Raman solitons was calculated using both the simulated output temporal durations and spectra. The efficiency with different chirp value of input pulse at three different average powers, i.e., 200 mW, 400 mW, and 600 mW are presented in Figure 4.8. The corresponding central wavelengths for these three output powers are 2.07 μm , 2.16 μm and 2.30 μm , respectively. The percentage of the energy that ends up in Raman solitons is related to the shape of the initial pulses. In addition, the chirp can increase the SSFS when the input pulses have positive chirp [19]. However, further increase of chirp value results in a larger pulse width and lower peak power. Therefore, the nonlinear induced frequency shift would be smaller.

Figure 4.8 The simulated efficiencies vs. the chirp value of pulses after DCF at different output power

According to the simulation results, higher conversion efficiencies can be obtained at the chirp value of 2.3 - 2.5. It corresponds to the length of DCF between 5.7 to 6m. From simulation, we observed that

the efficiency is influenced by input pulses, the Stoke's efficiency, and coefficients of TDF simultaneously. It is rare to achieve 100% efficiency. Moreover, it was assumed that the gain in frequency domain was only dependent on the emission cross sections of thulium ions. However, the energy level of Raman solitons is larger than that of remaining pulses. Thus, the actual gain coefficient for Raman solitons should be larger than that used in simulations. As a result, the calculated efficiency of energy transferred to Raman solitons in the simulation is expected smaller than experimental value especially for Raman solitons in longer wavelengths.

Figure 4.9 shows the pulse evolution in the TDF in frequency-domain and time-domain with 5.7 m DCF. The pulses are amplified first. After the peak power increased to form higher order solitons, the soliton fission happened. And due to the intra-pulse Raman shift, the soliton shifts to longer wavelength. In the material with anomalous dispersion, the light with longer wavelength has slower velocity. Thus, the Raman soliton separates from the original pulse in time-domain.

Figure 4.9 The pulse evolution in the 3.3 m TDF in frequency-domain (a) and time-domain (b) with 5.7 m DCF

4.3 Flat mid-IR supercontinuum pumped by a femtosecond TDF laser

In comparison with the alternative IR light sources, such as globars, lamps, synchrotron, fiber-based supercontinuum source offers attractive potential due to the high brightness and broad

spectrum rang [75]. The intrinsic losses of silica substrate limit the spectrum to $2.5\ \mu\text{m}$ [9]. In order to extend the SC to longer wavelength, soft glass fibers have been adopted. Heavy metal fluoride, such as ZBLAN fiber is one of the commonly used candidates due to its technological maturity, high glass stability and transparency in the mid-IR [10]. The popular fiber pumps sources are erbium doped fiber amplifier (EDFA) and TDFA. As ZBLAN fibers typically have zero-dispersion wavelengths (ZDW) between $1.65 - 1.9\ \mu\text{m}$ [11,12], pumping near $2\ \mu\text{m}$ results in both an extension of bandwidth and an increase of conversion efficiency towards mid-IR wavelengths [78].

SC generation in ZBLAN fiber has been widely reported. The widest spectral width achieved in ZBLAN was reported by G. Qin with the spectral coverage from UV to $6.28\ \mu\text{m}$ [78]. They used a 2 cm fiber length to decrease the fiber loss at the longer wavelength region, as the loss was larger than 100 dB/km when the wavelength was beyond $3.7\ \mu\text{m}$. The pump source they used was a 1450 nm femtosecond laser with 50 MW peak power from OPA. Thanks to the high peak power, the prodigious nonlinearities happened in such short fiber. However, limited by the pump source, the output SC average power was only 10 mW.

The record edge of SC in ZBLAN in shorter wavelength was reported by X. Jiang [79]. The SC spectrum after ZBLAN started from 200 nm. They used a $3\ \mu\text{m}$ core diameter ZBLAN photonics crystal fiber with a air-filling fraction to generate a SC spanning more than three octaves from deep UV to Mid-IR. An Ytterbium doped potassium-yttrium-tungstate laser delivering 140 fs pulses with 75 MHz repetition rate at a wavelength of 1042 nm was used as the pump source. The maximum available energy was 11.8 nJ. The pulses were launched into a 4-cm-long ZBLAN PCF using free-space optics with mirrors and lenses.

The longest edge for ZBLAN SC generation was reported by O. P. Kulkarni in 2011 [80]. A flat spectrum from $1.9 - 4.5\ \mu\text{m}$ was obtained by a two-stage SC generation. The amplified erbium doped fiber laser generated a SC to $2.1\ \mu\text{m}$ in a 25 cm long single mode fiber. The wavelength components at $2\ \mu\text{m}$ range were amplified in a TDF amplifier and launched into an 8.5m ZBLAN fiber after the amplification. Benefiting from the two-stage SC generation, a flat spectrum (whole spectrum within 10 dB) with high conversion efficiency at the long wavelength range ($\sim 27\%$ average power in wavelength $> 3.8\ \mu\text{m}$). O. P. Kulkarni also compared the SC generation pumping by EDFA and TDFA. Their results shown that TDFA based SC generation extended further to longer wavelength by 270 nm compared with EDFA based SC output.

Most of the implementation of SC generation in ZBLAN fiber pumped by TDFA is based on picosecond laser pumping. However, the typical shape of SC pumped by picosecond pulses in the anomalous dispersion region consists of a residual peak at the pump wavelength and the continuum forms about 10 to 20 dB below the pump peak [14]. This residual peak is the result of less dominating SPM effect. Pumping with femtosecond pulses will enhance the SPM process and transfer energy away from pump peak and thereby decrease the amount of residual pump light in the spectrum [81]. Thus, a flatter spectrum can be generated through pumping by femtosecond pulses. The flatness of supercontinuum is an important property for some application. For example, in infrared countermeasures, the ideal spectrum would be flat over the atmospheric mid-IR transmission windows [82]. Moreover, for femtosecond pump pulses, the grade of spectral coherence and the stability of phase are considerably higher than longer pulses. These two properties are crucially important for some applications such as optical frequency metrology and optical coherence tomography [83].

4.3.1 Experimental setup and results

The schematic of experimental setup is illustrated in Figure 4.10(a). A nonlinear polarization rotation based passively mode-locked fiber laser is used as the seeding oscillator. The optical pulses delivered by the oscillator are first amplified in a TDF pre-amplifier. As the next step, the pulses from the preamplifier, after optical isolation, are pre-chirped by passing an DCF fiber with NA of 0.41, core/cladding diameter of 2.4/125 μm and normal dispersion of -23 ps/km/nm [84]. The pulse train from the DCF fiber is then boosted in a TDF main amplifier, consisting of a 5 m single mode double-cladding TDF with core/cladding diameter of 10/130 μm , core/cladding NA of 0.15/0.46, and cladding absorption of 3 dB/m at 793 nm. A (2+1) $\times$ 1 pump combiner is used to deliver forward pumping light to the gain fiber from a fiber-pigtailed multimode laser diode operating at 793 nm. The output end of the main amplifier is fusion spliced to a section of 20 cm SMF-28 fiber, to filter out the residual pump. At last, the output end of the SMF-28 fiber is mechanically spliced to the input end of a 15 m ZBLAN fiber (FiberLabs Inc.) with a cleaved angle of 8° on both fibers to avoid back reflection. The ZBLAN fiber has core/cladding diameter of 6/125 μm and NA of 0.265. This ZBLAN fiber is customized to a small core and large NA to provide good confinement of the guided mode in the fiber core region [14]. The ZDW is 1.66 μm with a dispersion slope of 0.021 ps /nm²/km (calculated using OptiFiber). Figure 4.10(b) is the calculated dispersion curve of the ZBLAN fiber and the fiber loss is shown in Figure 4.10(c).

Figure 4.10 (a) The schematic experimental setup of the supercontinuum generation system; (b) the calculated dispersion curve of the ZBLAN fiber; (c) the loss of the ZBLAN fiber

In our experiment, the output power was measured with a wavelength insensitive thermal power meter (Ophir, 3A-FS). The SC spectra below 3400 nm were measured by two OSAs (YOKOGAWA, AQ-6315B, 350–1750 nm, and AQ 6375L, 1900–3400 nm) whereas that for longer wavelengths was acquired by using a Mid-IR spectrum analyzer (Bristol 771, 2–12 μm). The ultrafast pulse was characterized by a FROG (MesaPhotonics). A high speed digital oscilloscope with 2.5 GHz bandwidth (Agilent, DSO-X92504A) and a 12.5 GHz InGaAs photodetector (EOT, ET- 5000F) were used to measure time characteristics.

Figure 4.11 (a) The spectrum of the pulse after preamplifier. Insert shows the pulse train with a repetition rate of 56 MHz, (b) Pulse profile reconstructed by FROG after the preamplifier

Figure 4.11(a) shows the measured spectrum from the fiber preamplifier. The output power is 100 mW and the spectrum has a central wavelength of 1970 nm and a 3 dB spectrum bandwidth of 19 nm. The pulse duration is measured to be 918 fs, as shown by the FROG reconstructed pulse profile in Figure 4.11(b). The inset of Figure 4.11(b) shows the stable pulse train with a repetition rate of 56 MHz. To pre-compensate the anomalous dispersion induced by the fiber in the following amplifier, a 4 m UHNA fiber was spliced after the preamplifier with 80% coupling efficiency. More importantly, this UHNA fiber provides the precondition for ultrafast pulse generation. Due to the transform limited theory, shorter pulse width needs wider spectrum width. Shown in Figure 4.12, the 3 dB spectrum width was extended to 40 nm after the DCF fiber. This broadening is contributed by the larger nonlinear effect (SPM), and the larger nonlinear coefficient (about 8 times of that of standard single mode fiber) of DCF is resulting from its small core diameter.

Figure 4.12 The spectrum of pulse after broadened in UHNA fiber

The pulses with an average power of 69 mW, at the output of the fiber combiner, were launched to the double-cladding TDF to be further amplified up to 658 mW. The slope efficiency with respect to the coupled pump power was measured as 15%. During the amplification process in the power amplifier, the laser spectrum is gradually extended which is mainly initiated by the nonlinear effects of SPM and SRS [8]. The measured spectra at different output power levels (85 mW, 305 mW, 658 mW) are shown in Figure 4.13(a). As described in chapter 2.2.1, the SPM induced spectrum broadening is symmetrical. The invisibly symmetrical broadening in the central wavelength, 1970 nm, was due to the gain spectrum of the TDF. Figure 4.14 is the measured ASE spectrum of the TDF used in the experiment. The spectrum region before 1970 nm could not be amplified effectively in the TDF. Moreover, the spectrum component at the short wavelength would be reabsorbed by TDF. Thus, the spectrum broadening in the short wavelength region due to the SPM cannot be observed. The peaks in spectrum at the average power of 658 mW were induced by SRS. Calculating from Equation 4.1, the first and second order of SRS peaks are 2157 nm and 2383 nm, respectively. The experimental results satisfied the calculation.

Figure 4.13 (a) Output spectra and (b) pulses profiles at the average power of 85 mW, 305 mW, and 658 mW after the main amplifier

Figure 4.14 The measured ASE spectrum of the TDF

At the same time of pulse broadening, the pulse width is narrowed during the amplification process. Figure 4.13(b) shows the pulse profiles at these three powers. The full width at half maximum of the pulse was measured as 181 fs at the power of 658 mW, more than a compression factor of 5 with respect to the pulse width from preamplifier output. The consequent temporal compression can be understood as the higher order soliton pulse compression, which is the result of the interplay between SPM and anomalous dispersion [85-

87]. The fundamental soliton is generated when the SPM effect is just compensated by anomalous dispersion. When the compensation is imperfect, high-order soliton can be generated, for which it is possible to achieve self-compression when the sign of chirp induced by anomalous dispersion is opposite to that of SPM. For this reason, the pulse width could be compressed without other dispersion compensation elements (fiber or grating). Thus, during the pulse propagation in the TDF the nonlinear pulse compression can be achieved [68]. It should be noted that unlike dispersion effect, SPM effect is power dependent. Therefore, the compression factor changes with power for a fixed fiber length and the pulse width can be optimized by tuning the pump power.

The generated SC spectra are shown in Figure 4.15 as a function of output average power from the ZBLAN fiber. The maximum spectra bandwidth spanning from 1.1 to 3.7 μm is achieved for 253 mW average power with spectral flatness of 10 dB over a 1390 nm from 1940 – 3330 nm. The spectrum was bi-directionally broadened both to near- and mid-IR region as presented. The dip around 2.7 μm corresponds to OH^{-1} ions absorption in the ZBLAN fiber and in the unpurged (N_2) detection system.

Figure 4.15 ZBLAN output spectra generated at an average output power of 35 mW, 100 mW and 253 mW

As the femtosecond pulses pump experienced anomalous dispersion in the ZBLAN fiber, the 65 kW peak power was high enough to generate higher order solitons and initially undergo the expected evolution dynamics of spectral broadening and temporal compression [19]. However, the higher order effects, such as intra pulse Raman scattering and third order dispersion, act as perturbations, causing the fission of higher order solitons into the constituent fundamental solitons [88]. Different from the SC pumped by picosecond pulses where the main mechanism of spectral broadening is modulation instability (MI) and four wave mixing, it turns out that soliton fission plays a critical role in the formation of a supercontinuum pumped by femtosecond pulses [89]. The individual solitons have a relatively wide spectrum and are thus affected by intra-pulse Raman scattering that shifts the soliton spectrum toward longer and longer wavelengths with further propagation inside the fiber [19, 90]. As a result, many new spectral components are added on the long-wavelength side of the original pulse spectrum and form the mid-IR region of the SC. Moreover, during the soliton fission process, the presence of higher order dispersion can lead to the transfer of energy from the soliton to the phase matched non-soliton radiation. This radiation is called dispersive wave whose wavelengths fall on the shorter wavelength side in the normal dispersion region ($<1.66 \mu\text{m}$ for ZBLAN fiber used in the experiment) [91]. This dispersive wave dominates the shorter wavelength generation in the near-IR region.

4.3.2 Numerical simulation of flat supercontinuum generation

To verify this observation, pulse propagation simulation was carried out to calculate the output SC spectra pumped by pulses with different pulse width but same peak power, as shown in Figure 4.16(a). The detailed spectra at the pump wavelength region for these three situations are shown in Figure 4.16(b). Obviously, the residual peak is not present in the SC pumped with femtosecond pulses. However, the SC spectra pumped by picosecond and nanosecond pulses have 14 dB and 26 dB residual peak respectively.

Figure 4.16 (a) SC spectra pumped by femtosecond, picosecond and nanosecond pulses with the same peak power, (b) The magnification of the SC spectra near the pump wavelength

Figure 4.17 is the simulation results of the evolution of pulse propagating along ZBLAN fiber. It can be observed that in the first small distance, spectrum broadens due to SPM effect, and pulse narrows in time domain due to the soliton nonlinear compression at the same time. After the narrowest point in time domain, soliton fission appears. The dispersive wave is generated at the normal dispersion region (around 1000 nm) after the soliton fission. From the spectrum evolution in the whole fiber, higher-order SRS can be observed and the redshift due to soliton self frequency shift is obvious. As mentioned in chapter 2.2, shorter wavelength components travel faster than longer wavelength components in the anomalous dispersive medium. In the temporal evolution, six pulses in the trailing edge (corresponding to the peaks in longer wavelength in the spectrum) and one pulse in the leading edge (corresponding to dispersive wave).

Figure 4.17 (a) The simulation results of the evolution of pulse propagating along ZBLAN fiber, (b) The zoomed-in evolution in the first 0.15 m

From the spectrum presented in Figure 4.15 at the average power of 253 mW, we can observe that there is no significant residual peak at the pump wavelength, in contrast to the typical SC generation pumped by picosecond pulses for which the continuum forms 10-20 dB below the pump peak. The residual peak is due to the insignificance of SPM effect for using picosecond pumps [92]. In femtosecond regime, SPM would be expected to be strong because the Stokes-broadening is inversely proportional to the rise time of the laser pulses [93]. The enhanced SPM now becomes non-negligible during the nonlinear process. It can be reflected as spectrum broadening by transferring the energy from the pump to shorter and longer wavelengths continuously, which results in the flatter spectrum.

The ultrafast pulse pump can get high peak power of more than 50 kW at sub-watt average power level. Different with the SC generated in [94, 95] which requires high pump power (tens of watts), the SC generated by femtosecond pulse pumping can achieve octave-spanning with

sub-watt level, i.e. 658 mW. Thus, it is more efficient to achieve broadband SC using femtosecond pump, and avoid thermal issues raised by the soft glass fibers as well. The TDFA pulse can be improved to narrower pulse width and higher peak power by adjusting the 793 nm pumped power and the fiber length. A wider spectrum and a higher efficiency of long wavelength in the Mid-IR region can be achieved by optimizing the ZBLAN fiber (dimension, NA, and dispersion).

4.4 Conclusion

Making use of the nonlinearities in fibers, the application of using the ultrafast TDF laser to generate mid-IR sources is explored. A tunable laser with the high conversion efficiency up to 97% was generated in a TDF amplifier. The high conversion efficiency was achieved by optimization of input pulse chirp before the amplifier, which is verified by our simulation. The pulse width was kept below 200 fs. The central wavelength can be tuned from 1.98 to 2.31 μm . The achievable longest wavelength was limited by the cutoff of the silica material. A wider tunable wavelength range with high efficiency can be expected by replacing the thulium-doped host material from silica to soft glass, e.g., a fluoride fiber.

Except to the ultrafast lasers, we also demonstrated the supercontinuum generation. To the best of our knowledge, we for the first time obtained the supercontinuum generation pumped by sub-watt femtosecond pulses from a TDF amplifier. With a compact all-fiber pump laser with 181 fs pulses at average power of 658 mW, the supercontinuum source can demonstrate broadband flat spectrum coverage from 1100 to 3700 nm. The 10 dB bandwidth has a range over 1390 nm in the mid-IR region from 1940 – 3330 nm. From a practical point of view, generation of supercontinuum by pumping source with low average power demands less stringent specifications for all the optical components as well as the mid-IR waveguide. Moreover, such broadband coherent source offers great opportunity in applications such as LIDAR, spectroscopy and metrology.

Chapter 5 Pulse energy scaling of TDF laser in a CPA system

Producing ultrafast optical pulses with high pulse energy is necessary for a wide range of laser-matter-interaction research such as HHG. However, the high peak intensity would induce the nonlinear pulse distortion and fiber damage, if the ultrafast pulses are directly amplified to high pulse energy in fibers.

The optical breakdown threshold of fused silica limits the peak intensity below 10^{14} W/cm² [96], corresponding to 80 MW in conventional signal mode fibers. Moreover, the spatio-temporal structure of pulses can be strongly influenced by the high peak intensity induced nonlinearities. The self-focusing effects limits the peak power to 24 MW in the fused-silica fiber at 2 μ m [48]. The other nonlinearities, SPM and SRS, are unwanted in the high pulse energy fiber laser systems. They would shift the wavelength out of the designed bandwidth and the pulse quality would be degraded. Therefore, a lot of efforts go towards to mitigate these effects in energy scaling fiber lasers.

5.1 The principle of chirped pulse amplification

CPA is a technique for amplifying pulses to very high optical peak power (megawatt [97] to petawatt [98]) while avoiding excessive nonlinear pulse distortions or optical damage. The schematic of the CPA principle is shown in Figure 5.1. Before passing through the amplifier medium, the pulses are temporally stretched (linearly chirped) to a much longer duration (hundreds of picoseconds [99] to nanoseconds [100]) by means of a strongly dispersive element. This reduces the peak power to a level where the above mentioned detrimental effects in the gain medium are avoided. After amplification to a much higher pulse energy, a dispersive compressor with opposite dispersion is used to remove the chirp and temporally compress the pulses to a duration similar to the input pulse duration, so that extremely high peak intensity of the pulses can be obtained.

Figure 5.1 Schematic of the chirped pulse amplification

For a Tm-based fiber CPA laser system, the most outstanding performance referring to peak power was achieved by C. Gaida et. al. [100]. They presented a laser system delivering a pulse-peak power of 2 GW and a nearly transform-limited pulse duration of 200 fs in combination with 28.7 W of average power by using a rod-type fiber. The best results obtained in relatively compact systems are achieved using thulium-doped fiber master oscillator power amplifier (MOPA) systems operating at center wavelengths around 2 μm [101]. Pulses with 156 μJ pulse energy and 100 kHz repetition rate were obtained from the all-fiber MOPA system. With a grating pair compressor, the pulse width was compressed to 780 fs.

5.2 The CPA fiber laser system

The schematic diagram of the fiber CPA setup is illustrated in Figure 5.2. It contains an ultrafast oscillator, a stretcher, a pulse picker, 3 stages of amplifiers and a compressor based on CVBG. In order to make a compact system, free-space optics must be avoided. To achieve hundreds of micro-joule level pulse energy, the nonlinearity threshold is increased by stretching the pulse to nano-second by means of a chirped fiber Bragg grating (CFBG) stretcher and using large mode area fiber as the amplifier. The pulse picker was a fiberized acousto-optical modulator (AOM). The oscillator was an all-fiber NPE based mode-locking laser with 0.5 mW average power and 65 MHz repetition rate. It was described in chapter 2.

Figure 5.2 The schematic diagram of the fiber CPA setup

5.2.1 Stretcher and spectrum shaping

A commonly used pulse stretcher in fiber based CPA systems includes diffraction grating pairs, CVBG, CFBG or section of fibers. Grating pairs and CVBG have the advantages of providing a large amount of dispersion; the grating pairs can provide tens of ps^2 GDD [102] and the stretching factor of the CVBG can be larger than 20 ps/nm [99]. With such amount of dispersion, the pulse can be stretched to nanosecond level [102]. However, they require free space alignment. On the contrary, fiber based stretchers (CFBG and SMF), using the fiber splicing technology, can be perfectly embedded in the fiber system without extra alignment optics. The structure is therefore more compact. But fibers based stretcher, has limited stretched pulse width and spectral bandwidth. The GDD for 1m SMF at $2 \mu\text{m}$ is only around 0.1 ps^2 [84].

And the length of the fiber required for achieving comparable dispersion amount with grating pairs or CVBG is hundreds of meters. It would accumulate significant nonlinear phase shift, which is hard to be compensated by the compressor. CFBG is an ideal solution to provide large dispersion without introducing obvious nonlinear phase shift.

Fiber Bragg grating (FBG) is a distributed Bragg reflector [103] that is constructed in the optical fiber. The Bragg grating effect is achieved by the periodic variation of the refractive index in the fiber core. This reflection effect is wavelength-dependent. The reflection wavelength is determined by the Bragg condition:

$$\lambda = 2n_{eff}\Lambda \quad (5.1)$$

where λ is the vacuum wavelength, Λ is the grating period and n_{eff} is the effective refractive index.

When the refractive index profile is modified with a linear variation, i.e. by varying Λ linearly, the reflected wavelength changes with the grating period. Illustrated in Figure 5.3, along with the FBG, the different wavelength is reflected at different position and subject to different delay. As a result, the dispersion is introduced.

Figure 5.3 The schematic of a CFBG stretcher by reflecting different wavelengths at different locations along the grating axis (The blue line represents shorter wavelength)

The critical parameter of the CFBG can be described with spectral chirp rate (SCR, nm/cm) or stretching factor (SF, ps/nm).

$$SCR = \frac{d\lambda}{dz} \quad (5.2 \text{ a})$$

$$SF = \frac{2n_{eff}}{c \cdot SCR} \quad (5.2 \text{ b})$$

where z is the direction along the fiber. The stretched pulse duration affected by the CFBG can be calculated as,

$$\tau_{st} = \tau_0 + SF \cdot \Delta\lambda \quad (5.3)$$

where $\Delta\lambda$ is the bandwidth of the input pulses.

The stretching factor of the CFBG (Teraxion, PSR-1976-30-(-D100+0)) used in this experiment is designed as -100 ps/nm. The reflection efficiency is ~30% with 30 nm bandwidth. Figure 5.4 is the measured reflection spectrum and the group delay given by the specification of the CFBG. The relatively low reflectivity when positive chirp port is used is due to the coupling between core mode and cladding modes.

Figure 5.4 The measured reflectivity (left axis) and the group delay given (right axis) by the specification of the CFBG

The pulses were stretched to 1.5 ns after the CFBG. Temporal envelope of the stretched pulses was measured using a photodiode (EOT, ET- 5000F) with 12 GHz bandwidth and an oscilloscope (Tektronix, DPO70604C) with 6 GHz bandwidth. The temporal profile of the stretched pulses is shown in Figure 5.5.

Figure 5.5 The temporal profile of the stretched pulse

The spectral shape is mapped into the temporal profile due to large stretch factor. The ripples in the temporal profile induced by the non-smooth spectral reflection of the CFBG. By making use of the spectral-temporal relationship, the temporal pulse width can be further increased by trimming the spectrum. The spectral trimming was achieved by a PC and a PSISO. The PC changes the polarization of the light and the PSISO works as the polarizer. This combination plays the role of a wavelength-dependent filter. Thus, by tuning the PC, the spectra can be shaped. This pulse shaper utilized the Lyot filter effect (described in Chapter 2). The shaped spectrum and the corresponding temporal shapes are shown in Figure 5.6. The purpose of this spectral shaper is not only to increase the pulse width of the temporal profile, but also to pre-compensate the lower gain of the power-amplifier.

Figure 5.6 The temporal profile (a) and spectral shape (b) of the pulse shaped by the PC and PSISO

5.2.2 Three-stage amplifier

After the oscillator, a double-pass amplifier (Amp1) was placed to pre-compensate the loss that would be incurred from the fiber based AOM in next stage. The amplifier consisted of a single mode double cladding TDF (DC-TDF) with a core diameter of 10 μm and a length of 2 m, an optical circulator and the CFBG as the reflector. Two 793 nm multimode fiber coupled laser diodes with 12 W maximum power were used as the pump source. When the pulses once pass through the TDF, they are reflected by the CFBG and amplified in the TDF again. The input signal is amplified in both forward and backward pumping. The double-pass amplifier has much improved gain performance with a relative low ASE. The gain can be increased to more than 10 dB compared with single-pass amplifier gain [104]. After the amplifier, more than 32 dB gain was achieved with 4.8 W pump power. The average power increased to 800 mW, corresponding to 12 nJ pulse energy. The spectral shaper made of the PC and the PSISO was placed after the Amp1. As the spectral shaper is based on the spectral filter effect, it would induce loss. The average power was reduced to 230 mW, corresponding to 3.5 nJ pulse energy, after the spectral shaping.

In order to amplify the pulse energy to several hundreds micron-joule with limited pump power, a fiber coupled AOM (Brimrose, IPM-250-50-10-10-1970-2FP) was used to reduce the laser

repetition rate. Based on the acoustic-optic effect, the sound waves modify the refractive index by oscillating mechanical pressure, the AOM is able to modulate the repetition rate of the light. The laser repetition rate was reduced from 65 MHz to 100 kHz. The AOM was driven with synchronized electrical signal from oscillator. The measured insertion loss of the AOM is around 7 dB. After the AOM, pulses with 0.7 nJ pulse energy and 100 kHz repetition rate were delivered to the second double-pass amplifier (Amp2).

The Amp2 has the same configuration as Amp1, but with all polarization maintaining fibers. The signal with linear polarization status is required in the compression stage, and the laser operation is more stable compared with using non-polarization maintaining fibers. The CFBG2 (OEland, OECFBG-100) used in Amp2 has 8.3 ps/nm stretching factor. Different from CFBG used in Amp1, the main functions of the CFBG in Amp2 are the reflector and the ASE filter. The reason of using negative dispersive CFBG here is that grating has a reflectance as high as 99%. The ASE generated in Amp2 was not negligible due to the relatively low repetition rate (100 kHz) and seeding power (70 μ W). The CFBG with limited bandwidth can filter the ASE out of the reflection bandwidth. After the Amp2, the pulses are amplified to 280 nJ pulse energy.

Detrimental nonlinear effects and lower power-damage thresholds make small-core fibers difficult and limit their use at high pulse energy and peak power. To overcome these limitations, in particular for the construction of high power fiber lasers and amplifiers, LMA and high doping concentrations have been proposed. For the conventional step index fibers, the core area with single mode operation is limited by the core NA. It is hard to achieve the NA smaller than 0.06. For example, with a core diameter of 25 μ m [75], the fiber is normally a few-mode fiber, which degrade the beam quality and amplification stability [105].

The double-clad LMA active PCF technology can fulfill these requirements and achieve the large effective area and single mode operation simultaneously. It is feasible to design and manufacture large mode field area and inner cladding numerical aperture according to the requirements. This type of fiber consists of a solid core and an inner cladding with a periodic air hole structure. Due to the addition of air holes, the inner cladding has a smaller effective refractive index than the core. That is, the core NA can be ultralow since air hole inner cladding structure. The outer cladding adopts a larger air hole to form a larger refractive index contrast, thereby increasing the numerical aperture of the inner cladding and improving the coupling efficiency of the pump light. What's more, the asymmetric arrange of the air holes can induce

the stress applying parts (SAP) and induce the birefringence to achieve polarization maintaining property.

Figure 5.7 is the schematic and scanning electron microscope (SEM) result of the cross section of the Tm-doped PCF used in the experiment. The solid core with 50 μm diameter and 0.04 NA is surrounded by hexagonal air hole lattice. The diameter of the air outer cladding is 250 μm with 0.45 NA. The overall fiber diameter is 550 μm , coated by a single layer polymer. The pump absorption for 793 nm by cladding pumping is ~ 5.6 dB/m. The mode field diameter for this fiber is 36 μm with more than 1000 μm^2 mode field area.

Figure 5.7 The schematic and SEM result of the cross section of the Tm-doped PCF

A 2.5 m PCF was forward pumped by six 32 W LDs (DILAS) centered at 793 nm through a $(6 + 1) \times 1$ fiber combiner. A 30 cm double cladding bridging polarization maintaining fiber with the core/cladding diameter of 30/250 μm was spliced between the combiner output fiber and the PCF to implement an all-fiber CPA system. The splicing point is shown in Figure 5.8. In order to provide the single mode operation, the PCF was coiled with a coiling diameter of 45 cm. Technically, the PCF is not a single-mode fiber. However, it provides single mode operation with bending diameter < 80 cm. But the fundamental mode loss has been observed with bending diameter < 35 cm [106]. The PCF was cooled by circulating water at constant temperature of 12°. The cooling system can remove the heat and allow this amplifier working with several hundreds watts of pump power. More importantly, proper cooling can improve the slope efficiency [102].

Figure 5.8 The splicing point between the PCF and the bridging fiber

The damage threshold at the glass/air interface is much lower compared with the laser induced material damage threshold. It is 5 GW/cm^2 [75] for fused silica fibers. In order to reduce the intensity at the PCF end-point, an endcap was spliced with the PCF. The endcap was 1.5 mm long with $550 \mu\text{m}$ diameter. It was angle cleaved at 8° to prevent the Fresnel reflections at the glass/air interface coupling back to the fiber core.

Figure 5.9 (a) Power performance of the 100 kHz CPA system, inset: the beam profile of the PCF output (b) Spectra recorded at different output power

When the pump power was 205 W, the amplified output power from PCF, at 100 kHz repetition rate, was 38.4 W with 23.7% optical-to-optical slope efficiency. Figure 5.9 (a) is the PCF output power changes with the pump power. The inset picture is the beam profile of the PCF output measured by a mid-IR camera (WinCamD-IR-BB, DataRay). The elliptical shape of the beam profile was due to the birefringence of the PCF. That is, the NA of the PCF is not exactly the same in the two orthogonal directions due to the SAP. The output spectra at different power

measured by OSA were presented in Figure 5.9 (b). As the power increased, the spectrum broadening due to the accumulated nonlinearities. The nonlinearities shifted the energy from the signal to the longer wavelength. For the wavelength beyond 2.1 μm , it was out of the gain spectrum of the PCF. Thus, the amplification efficiency decreased at high power.

The nonlinear effects that dominate the spectrum broadening are SRS and MI, while the SPM induced broadening was not significant.

In the case of strong stretching of the pulses, the frequency broadening due to SPM in the amplifier can be expressed as [107]:

$$\frac{\delta\omega_{max}}{\delta\omega_{1/e}} = \sqrt{\frac{1}{e} \frac{B}{\phi^{(2)} \times \delta\omega_{1/e}^2}} \quad (5.4)$$

where $\delta\omega_{max}$ is the new generated frequency, $\delta\omega_{1/e}$ is the half bandwidth at 1/e of the original spectrum, B is B-integral in the amplifier and $\phi^{(2)}$ is the second derivative of the stretching phase (the GDD induced by the stretcher). Considering the two CFBG used, the stretching factor is 91.7 ps/nm, corresponding to 190 ps² of $\phi^{(2)}$. And the $\delta\omega_{1/e}$ is 1.54 THz. According to the Equation 5.4, the ratio between the new generated frequency and the original bandwidth is:

$$\frac{\delta\omega_{max}}{\delta\omega_{1/e}} \approx 0.0075B \quad (5.5)$$

The calculated B is around 4 rad when the pulse energy amplified to 300 μJ . Thus, the spectral broadening due to SPM can be neglected.

The Figure 5.9 (b), the asymmetrical broadening attributes to SRS. The SRS effects transfer the energy from the original spectrum to longer wavelength. The Raman gain spectrum of the silica has the maximum value at 13.2 THz. A part of energy of central wavelength (1980 nm, corresponding to 151.5 THz) of the original spectrum shifts to 138.3 THz. The peak around 2.16 μm corresponds to the first SRS peaks.

The MI results from the interaction between the signal and the perturbations in time domain and broadens the spectrum symmetrically. The perturbation can be induced by the ASE generated in the amplifier or the un-flat reflection spectrum of the CFBG. The maximum gain of the MI is [19]:

$$G(\text{dB})_{\text{max}} = 4.34 \times 2B \quad (5.6)$$

In the amplifier with 4 rad B-integral, the maximum gain of the MI is larger than 30 dB. Moreover, the MI would interact with SRS in the longer wavelength. The MI effects would enhance the SRS effect.

The spectra indicate that the nonlinearity is a big issue. In the fiber amplifier with forward pumping, the most nonlinearities are accumulated in the latter half of the fiber and the seeding pulse energy also influences the total nonlinearities. Thus, the length of the PCF and the seeding pulse energy should be optimized to reduce the nonlinearities in the future work.

5.2.3 Chirped volume Bragg grating based compressor

In addition to the main amplifier for power scaling, another key component in CPA system is the compressor. Even though the fiber based dispersion elements are the ideal solutions for implementing a rigorous all-fiber CPA system, the current fiber-based compressors still have problems to sustain high peak power due to the small core area. Typically, grating pairs and CVBG are used as a compressor because they can handle relatively large beam size in free space. They can withstand high peak power while providing much larger amount dispersion.

Grating pairs are widely used in a CPA system. When the angle of the incident light and the grating is fixed, the direction of the diffracted light changes depending on the wavelength. The compensated dispersion amount can be flexibly adjusted by changing the distance between the two gratings [108].

The principle of the CVBG (shown in Figure 5.10) is similar to the CFBG, but writing the Bragg structure in bulk materials. It can accept large beam size (several millimeters), and the beam diameter could be 2 orders of magnitude larger than the beam size in CFBG. As a result, the CVBG can sustain much higher peak power. It can support a peak power up to 4 GW using the CVBG at 2 μm wavelength range [109].

Figure 5.10 The schematic of the CVBG operation

The dispersion amount provided by CVBG is decided by the Bragg structure period, and cannot be adjusted. However, compared with using grating pairs, the compressor based on CVBG is compact and alignment insensitive. Using the commercial grating pairs with 560 lines/mm groove density and 34° Littrow angle, the distance between the two gratings is around 14 m in order to compensate the dispersion provided by the stretcher in the previous stage. With such a distance between the two gratings, the beam size at the second grating would be larger than 50 mm. no commercial grating can provide such large size. Using CVBG, the footprint of the compressor can be shrunk down to $45 \times 45 \text{ cm}^2$.

The specifications of the CVBG (Optigrate, CBG-1977-90-M) used are listed in Table 5.1.

Table 5.1 Key parameters of the CVBG used in the experiment

Design wavelength	1977.5 nm
Bandwidth (FWHM)	36 nm
Diffraction efficiency	94%
Cross section aperture	5 mm × 10 mm
Stretching factor	-22.8 ps/nm

The compressor was 4-pass configuration based on two CVBGs shown in Figure 5.11. The signal after the power amplifier is collimated by a lens with 40 mm focal length. A high power free space isolator was placed before the compressor to prevent the light reflects by the optics in the compressor back to the amplifier. A half wave plate (HWP) was set after the isolator to

adjust the polarization direction of the signal. The incident angle between the light and the grating was adjusted by two highly reflected mirrors (HRM). The light reflected from the CVBG was reflected by another HRM and returned to the path it came. This double-pass configuration in the same grating not only increases the dispersion, but also remove the spatial chirp. The reflection and transmission of the beam are controlled by an optical combination. This combination contains the quarter wave plate (QWP) and the thin film polarizer (TFP). Passing through the QWP twice, the polarization direction of the light changes 90° . Thus, the output can be distinguished with the input. The last two passes for the second grating have the same configuration as the first one.

Figure 5.11 The four-pass compressor configuration

The overall efficiency of the four-pass compressor at different power was shown in Figure 5.12. The efficiency was 46.5% at low average power. As the power increased, the efficiency dropped significantly. When the input power was higher than 10 W, the output power decreased even though the input power increased. There were two reasons that caused such low efficiency, the material absorption and spectrum-clipping.

Figure 5.12 The overall efficiency of the four-pass compressor at different power

The measured one-pass efficiency of the CVBG was 85% of the signal with 1980 nm central wavelength, which is lower than the given diffraction efficiency (94%). This lower efficiency was due to the material absorption. The spectral comparison of the input and output reflected by the CVBG was presented in Figure 5.13. The longer wavelength experienced more significant loss. The CVBG has anomalous dispersion, so the longer wavelength propagates deeper in the CVBG. That is, more absorption is experienced by longer wavelength.

Figure 5.13 The spectral comparison of the input and output reflected by the CVBG

Spectrum-clipping is the dominant reason for the efficiency decreasing. The reflection bandwidth of the CVBG is limited. The spectral component out of this bandwidth could not be reflected by and would pass through the CVBG. Figure 5.14 (a) is the input spectrum at 10W average power and the output spectrum reflected by the CVBG. The broadened spectrum component before 1960 nm and after 1995 nm was filtered. The measured average power of the filtered spectrum (pass through the CVBG) was shown in figure 5.14 (b). By integrating the spectrum, the ratio of the spectral component in the CVBG bandwidth (1960 nm to 1995 nm) was 73%. It is very close to the measured CVBG transmission power (29% loss at 10 W input average power).

Figure 5.14 (a) the input spectrum at 10W average power and the output spectrum reflected by the CVBG, (b) The measured average power of the filtered spectrum

With 10 W input power, the loss induced by material absorption and spectral-clipping for the four-pass configuration were 2.82 dB and 1.55 dB respectively. By considering the loss and the efficiency of the optics (Table 5.2), the efficiency was calculated as 34.3% at this power level. And the measured four-pass efficiency was 33.0% at 10 W input power, which was very close to the calculation

Table 5.2 The measured efficiency of the optics used

Optics	HWP	QWP	HRM
Measured efficiency	99.64%	99.09%	99.1%

In practical case, the refractive index of the CVBG in vertical direction is not uniform. The refractive index has a graded profile throughout the thickness of the grating due to the intrinsic absorption of the illuminating UV light during the fabrication process. A collimated beam deflecting results from the propagating in a graded refractive index medium. Figure 5.15 illustrates this effects.

Figure 5.15 Beam propagation in a gradient index CVBG

Due to the graded index profile, the output beam of the compressor has an elongated shape (Figure 5.16(a)) and spatial chirp (the non-uniform frequency distribution). By reversing the first CVBG upside down to pre-compensate this effect, the beam elongation was released (Figure 5.16(b)). Figure 5.16 presents the output beam profile (with 10 W input power) after the CVBG reversing. However, the highlighted spatial chirp was not solved.

Figure 5.16 The beam profile before (a) and after (b) the first CVBG reversing

The compressed pulse duration was characterized by FROG. In the FROG, the beam was split to two by a D shape mirror and the two arms generated a second harmonic in a BBO crystal. Thus, the spatial chirp of the beam would affect the FROG measurement. In order to mix the frequency components in space, the output of the compressor was coupled to a 50 cm hollow core fiber (HCF) [110]. The ultra-low dispersion ($2 \text{ ps}^2/\text{km}$) of the HCF has negligible influence on the pulse width. The spectrum of the laser was also not affected by the HCF because of the transmission in air and wide transmission bandwidth (1700 nm to 2100 nm).

The total propagation distance of the laser from the PCF to the HCF was about 2 m. After the propagation, the laser beam diameter increased to 3.2 mm from 2.7 mm (the focal length of the

collimation lens after the PCF is 40 mm). The laser beam was coupled by a plano-convex lens with 50 mm focal length to the HCF. The calculated beam diameter and divergence of the focal beam was $46\text{ }\mu\text{m}$ and 0.07 mrad . The mode field diameter and NA of the HCF is $32\text{ }\mu\text{m}$ and 0.038 . Thus, it cannot efficiently couple the laser to the HCF. And not all frequency information was coupled to the HCF due to the spatial chirp. By shifting the overlap between the focal beam and the core of HCF, the output spectrum from the HCF is different.

Figure 5.17 presents the retrieved temporal profile (blue curve in 5.17 (a)) and spectrum retrieved from FROG (blue curve in 5.17 (b)) and the OSA measured spectrum (red curve in 5.17 (b)) in one coupling condition. The measured and retrieved FROG traces are presented in Figure 5.18. The FROG error was 0.9%.

Figure 5.17 (a) The retrieved temporal profile (blue curve) and transform-limited pulse (red curve), (b) spectrum retrieved from FROG (blue curve) and the OSA measured spectrum (red curve)

Figure 5.18 The measured (a) and retrieved (b) FROG traces

The red curve in Figure 5.17(a) is the transform-limited pulse of the spectrum measured by OSA. The transform-limited pulse width is 0.9 ps. The discrepancy between the measured pulse width and this value could result from the uncompensated higher order dispersion and the nonlinear phase shifted. The measured TBP is 1.5 times of the transform-limited value. We can expect that the pulse width is around 500 fs for the whole laser spectrum.

5.3 Conclusion

We studied the pulse energy scaling in a polarization maintaining TDF CPA system in this chapter. A CFBG play the role of pulse stretcher to obtain a compact system. The double-pass configuration cooperating with a CFBG in the first two amplifier stages increased the gain and reduce noise simultaneously. The power amplifier was based on the LMA thulium-doped PCF; the highest output pulse energy was 384 μJ from the all-fiber amplifier. To the best of our knowledge, this is the highest pulse energy achieved from all-fiber TDF amplifier so far. After the amplification, the pulses were compressed to sub-ps level based on CVBGs. We also discussed and analyzed the reason of relative low efficiency ($\sim 30\%$) of the compressor.

There are still remaining issues to be optimized in this CPA system. The nonlinearities broaden the spectrum out of the usable bandwidth and waste more than 30% of the energy at the highest pulse energy. This issue can be reduced by optimize the seeding pulse energy and the active fiber length of the thulium-doped PCF amplifier.

The output pulse width after the compressor was not directly measured due to the spatial chirp. How to eliminate the beam deflecting due to the gradient refractive index and how to coupling the laser to the HCF effectively are still in investigation.

Chapter 6 Conclusion and future work

6.1 Conclusion

A detailed study of ultrafast TDF lasers was carried out both experimentally and numerically. The work presented in this thesis is summarized in the following.

Firstly, the all-fiber TDF mode-locked oscillator based on the NPE mechanism was developed and studied. A compact thulium-doped all-fiber mode-locked laser based on a hybrid OC-PSISO-WDM fiber device was demonstrated. The all-anomalous dispersion fiber ring cavity was minimized to 80 cm with a total dispersion of -0.045 ps^2 . The laser delivered 330 fs mode-locking pulses at a 248 MHz fundamental repetition rate. The novelty is the dispersion-compensation-free solution for a 2 μm sub-500 fs compact oscillator design. This oscillator exhibits a high SNR and long-term stability. Moreover, the fiber-based Lyot filter enables the wavelength tuning in this oscillator. The tunable range is as large as 143 nm (1867 nm to 2010 nm). To the best of our knowledge, it is the widest in femtosecond mode-locked TDFs so far.

Secondly, based on the dispersion and nonlinearity management, we achieved 65 fs pulses in a compact all-fiber laser system. The passive and active fiber chain effectively broadened the spectrum and compressed the pulses. Numerical simulation based on the split-step Fourier method was carried out to investigate the formation and evolution of the ultrafast pulses. A shorter pulse duration is expected when the proper HNLF fibers is designed and adopted.

Thirdly, we explored the application of the ultrafast TDF lasers to generate mid-IR pulses covering a wide wavelength range. We have demonstrated for the first time, supercontinuum generation pumped by sub-watt femtosecond pulses from a thulium doped fiber amplifier. With a compact all-fiber pump laser with 181 fs pulses at average power of 658 mW, the supercontinuum source can demonstrate broadband flat spectrum coverage from 1100 to 3700 nm. The 10 dB bandwidth has a range over 1390 nm in the mid-IR region from 1940 to 3330 nm. We also presented the tunable Raman soliton generation with the high efficiency up to 97% in a TDF amplifier. The high conversion efficiency was achieved by optimization of input pulse chirp before the amplifier, which is verified by the numerical simulation. The pulse width was kept below 200 fs through out of the tuning range. The central wavelength can be tuned from

1.98 to 2.31 μm . The achievable longest wavelength was limited by the cutoff of the silica material.

Lastly, we developed an all-fiber polarization maintaining CPA system besides the pulse compressor. We used the double-pass configuration in the first two stage amplifiers to improve the gain. The pulse energy was scaled to 384 μJ in the power amplifier based on a LMA thulium-doped PCF. After the amplification, the pulse was compressed by compact CVBGs.

6.2 Future work

6.2.1 Further optimization of the CPA system

In the current CPA system, several aspects can be optimized to further improve the laser performance, the nonlinearity control in the main amplifier, the solution for the spatial chirp of the compressor output and the high-order dispersion compensation of the whole CPA system.

In the fiber amplifier with forward pumping, the pulse energy evolution along the fiber can be illustrated in Figure 6.1. and the induced nonlinearity during the amplification process can be reflected by the value of B-integral.

Figure 6.1 The schematic of the pulse energy evolution along the active fiber length

The B-integral is defined as:

$$B = \frac{2\pi}{\lambda} \int n_2 I(z) dz \quad (6.1)$$

In fiber lasers, $I(z)$ is the peak intensity which equals to the peak power over the mode field area of the fiber. And z is the direction along the fiber. If the pulse width was assumed unchanged, the Equation 6.1 can be expressed as:

$$B = \frac{2\pi}{\lambda} \int n_2 \frac{E(z)}{\Delta t A_{eff}} dz \quad (6.2)$$

where $E(z)$ is the pulse energy, Δt is the FWHM pulse width and A_{eff} is the effective mode field area of the fiber. $\int E(z)dz$ is the grey area under curve in Figure 6.1; thus, the B-integral is proportional to this shadow area. It can be observed that most nonlinearities are accumulated at the end of the active fiber. And the pulse energy may be saturated at the end of the active fiber, that is, little gain is generated. Thus, the active fiber length is a key parameter in the power-amp. By simulating the GLE in the PCF, the fiber length can be optimized to maintain the output pulse energy and also decrease the nonlinearities to the blue shadow area in Figure 6.1.

The spatial chirp of the compressor output beam would induce problems of measurement, coupling, and further utilization of the laser. In order to solve this issue, the spatial chirp should be measured first. If the spatial chirp is linear, this issue can be eliminated by a prism pair. The spatial chirp elimination is illustrated in Figure 6.2. If it is not, the single coupling lens should be replaced by a lens set to couple the laser to the HCF more effectively.

Figure 6.2 The illustration of the spatial chirp elimination by a prism pair

The dispersion management in the CPA system was based on group velocity dispersion of the fiber used and the stretching factor of the CFBG and the CVBG. That is, only second order

dispersion was considered. Practically, the TOD is determinant on the pulse shape, peak power and the pulse broadening for femtosecond pulses. These parameters affect the further applications of the CPA laser, e.g. nonlinear pulse compression and HHG. The CFBG and CVBG are designed with zero TOD. However, the TOD of all the fibers (SMF, DC-TDF and PCF) used are positive. In the future, using the fiber with positive TOD (e.g. UHNA7) or the CFBG with positive TOD can be considered to compensate the total TOD in the CPA system.

6.2.2 High repetition rate TDF laser with ultrafast pulse width and high average power

Referring to the pulse energy scaling, the fiber laser have inherent ceiling compared with solid lasers [111-113] due to the small mode field area ($< 3300 \mu\text{m}^2$ [97]) and long active length (meter level). Even with the design of the LMA active fiber, the pulse energy is hard to scale to milli-joule level. Thanks to the coherent beam combining (CBC) technology, the highest pulse energy achieved was 12 mJ [114]. The pulses have 700 W average power and 262 fs pulse width. The system is complex containing 8 amplifier channels and 4 pulse replicas.

However, the small mode confinement and long length provide fibers the ability of good thermal management. Based on the theory discussed in chapter 3, an all-fiber laser with high repetition rate (hundreds MHz), high average power (hundreds watts), and ultrashort pulse width (femtosecond) is feasible. To achieve the objective, the key challenges are controlling the dispersion precisely and understanding the high power ultrafast pulse evolution in different fibers.

List of Publications

Journal article

- **Jiaqi Luo**, B. Sun, J. H. Ji, E. L. Tan, Y. Zhang and X. Yu, “High-efficiency femtosecond Raman soliton generation with a tunable wavelength beyond 2 μ m”, *Optics Letters*, 2017
- **Jiaqi Luo**, B. Sun, J. Liu, Z. Yan, X. Yu, “Mid-IR supercontinuum pumped by fs thulium doped all-fiber amplifier”, *Optics Express*, 2016
- Elizabeth Lee, **Jiaqi Luo**, Biao Sun, Vincent Ramalingam, Ying Zhang, Qijie Wang, Fei Yu, and Xia Yu, "Flexible single-mode delivery of a high-power 2 μ m pulsed laser using an antiresonant hollow-core fiber," *Optics Letters*, 2018
- X. Jin, E. Lee, **Jiaqi Luo**, B. Sun, V. Ramalingam, Q. Wang, Y. Zhang, P. Zhou, X. Yu, “High-efficiency ultrafast tm-doped fiber amplifier based on resonant pumping”, *Optics Letters*, 2018
- B. Sun, **Jiaqi Luo**, X. Yu, Q. Wang, “65 fs pulses at 2 μ m in a compact Tm-doped all-fiber laser by dispersion and nonlinearity management”, *IEEE Photonics Technology Letters*, 2017
- B. Sun, **Jiaqi Luo**, X. Yu, Q. Wang, “1867-2010nm femtosecond Tm-doped all-fiber laser”, *Optics Express*, 2017 (Top download in *OE*).
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- Z. Yan, B. Sun, X. Li, **Jiaqi Luo**, P. Shum, X. Yu, Q. Wang, “Widely tunable Tm-doped mode-locked all-fiber laser,” *Scientific Reports* 2016.

Conference proceeding

- **Jiaqi Luo**, B. Sun, E. L. Tan, X. Yu, “Compression of the high-power picosecond laser with chirped volume Bragg gratings”, oral presentation, HPLSE 2018. (Best student oral award)
- **Jiaqi Luo**, B. Sun, J. Ji, E. L. Tan, X. Yu, “Highly efficient tunable Raman Soliton by optimized chirp at 2 μ m”, poster, CLEO 2017.
- **Jiaqi Luo**, B. Sun, J. Liu, Z. Yan, X. Yu, E. L. Tan, “Mid-IR supercontinuum generation pumped by femtosecond pulse thulium doped fiber amplifier”, oral presentation, MICS, 2016.
- **Jiaqi Luo**, B. Sun, J. Liu, X. Yu, E. L. Tan, “Fiber based dispersion management for ultrafast pulses at 2 μ m”, oral presentation, ICMAT, 2015.

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