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PASSIVELY MODE-LOCKED FIBER LASER

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

2010

Statement of Originality

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

11/Jun/2010

Date

Tian Xiaolong

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Summary

Passive mode-locking is the routine technique to generate ultra-short optical pulses with fs~ps pulse width. As fiber lasers have the advantages of low cost and good robustness, they become attractive supplements of traditional solid state lasers. Hence, the investigation on the passively mode-locked fiber laser is of strong motivation.

Conventionally, the soliton mechanism was thought to be the domination of the pulse shaping in passively mode-locked fiber lasers. However, recent research demonstrated that the dissipative components such as the spectral filters can provide strong pulse shaping mechanism. In this thesis, the dynamics of the pulse shaping according to the dissipative devices in the laser cavity was investigated.

As a start, I investigated the effect of the saturable absorber in a passively mode-locked fiber laser with a dispersion managed laser cavity. It showed that by changing the properties of the saturable absorber, the laser can be mode-locked according to different pulse shaping mechanism in the same laser cavity. By applying nonlinear polarization rotation technique as an artificial saturable absorber, multiple stable mode-locking regimes have been observed. Noise-like emission was also achieved experimentally by adjusting the saturable absorber. A correct setting of the NPR module could lead to high energy noise-like pulse emission. A dual-wavelength mode-locking has been demonstrated by employing polarization maintaining fiber (PMF) in the laser cavity. Incorporating with the NPR mode-locking, ultra-short pulse emission at two distinct central wavelengths was achieved simultaneously.

Then the limitation to the pulse energy in an all-normal-dispersion passively mode-locked fiber laser was investigated. Such a laser has the advantage of high pulse energy compared to the conventional soliton lasers. However, the energy was still limited by the multiple-pulsing effect and the noise-like emission. I investigated mechanism of the both effects and found that the spectral filtering effect induces multiple pulsing through a pulse energy clamping mechanism. An analytical model was developed and showed that the pulse energy and the pulse bandwidth can be increased by increasing the modulation depth of the saturable absorber. The noise-like emission is caused by the wave-breaking effect. By optimizing the net dispersion of the cavity and the properties of the saturable absorber, high pulse energy with broad bandwidth can be achieved. Experimental results confirmed the theoretical prediction and high energy, broad bandwidth optical pulse has been achieved. The complex spectral filtering effect of the erbium doped fiber (EDF) was investigated. A switching between two mode-locking states at different central wavelengths could be observed. The two gain peaks of the EDF acted as two distinct bandpass filters (BPF) in the passively mode-locked fiber laser with all-normal-dispersion laser cavity.

To further investigate the pulse shaping function of the saturable absorber, I proposed and demonstrated a high pulse energy, ultra-low repetition rate mode-locked fiber laser. Without any discrete grating pairs or spectral filters, the laser could be stably mode-locked with sub-MHz repetition rate and output over 6 nJ optical pulses with hundreds of ps pulse width. Such laser can be applied in high resolution light detection and ranging system which requires sub-ns pulse and sub-MHz repetition rate. The experimental result also disclosed a novel pulse shaping mechanism of all-normal-dispersion mode-locked fiber lasers.

List of Publications

- [1] **Xiaolong Tian**, Ming Tang, Perry Ping Shum, Yandong Gong, Chinlon Lin, Songnian Fu, and Taishi Zhang, “High energy laser pulse with sub-MHz repetition rate from a passively mode-locked fiber laser”, *Optics Letters*, **32**, 1432-1434, 2009
- [2] **Xiaolong Tian**, Ming Tang, Xueping Cheng, Perry Ping Shum, Yandong Gong, and Chinlon Lin, “High-energy wave-breaking-free pulse from all-fiber mode-locked laser system”, *Optics Express*, **17**, 7222-7227, 2009
- [3] **Xiaolong Tian**, Ming Tang, Ping Shum and Yandong Gong, “Low repetition rate passively mode-locked fiber laser”, *Conference on International Conference on Advanced Infocomm Technology*, 2008
- [4] **Xiaolong Tian**, Ming Tang, Ping Shum and Yandong Gong, “Mode-locked fiber laser with large normal net dispersion”, *Conference on International Conference on Advanced Infocomm Technology*, 2008
- [5] **Xiaolong Tian**, Ming Tang, Yandong Gong, Perry Ping Shum, “Repetition rate switching in a passively mode-locked fibre laser”, *Asia-Pacific Optical Communications*, AOC06-APOC01-152, 2006
- [6] **Xiaolong Tian**, Yandong Gong, Perry Ping Shum, Ming Tang, “Multi-stable mode-locking states in a stretched passively mode-locked fiber ring laser” *International Conference on Optical Communications and Networks*, 2006
- [7] Yandong Gong, **Xiaolong Tian**, Ming Tang, Perry Ping Shum, M.Y.W. Chia, V. Paulose, Jie Wu and Kun Xu “Generation of dual wavelength ultrashort pulse outputs from a passive mode locked fiber ring laser.” *Optics Communications*, **265**, 628-631, 2006.

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List of Abbreviations

ANDi-laser	All-normal-dispersion passively mode-locked fiber laser
AM	Amplitude modulation
APL	Additive pulse limiting
ASE	Amplified spontaneous emission
BPF	Bandpass filter
CW	Continuous-wave
CPA	Chirped pulse amplification
DCF	Dispersion compensating fiber
DSF	Dispersion shifted fiber
DWDM	Dense-wavelength-division multiplexing
EDF	Erbium-doped fiber
FHWM	Full width at half maximum
FM	Frequency modulation
FPF	Fabry-Perot Filter
FSR	Free spectral range
FWM	Four wave mixing
GLE	Ginzburg -Landau equation
HNLF	Highly nonlinear fiber
LD	Laser diode
LIDAR	Light detection and ranging
LMA	Large mode area
LT-MBE	low-temperature molecular beam epitaxy
NLSE	Nonlinear Schrödinger equation
NOLM	Nonlinear optical loop mirror
NPR	Nonlinear polarization rotation
OSA	Optical spectrum analyzer
OTDM	Optical time division multiplexing
PC	Polarization controller
PCF	Photonics crystal fiber
PMF	Polarization maintaining fiber
PZT	Piezo-electric transducer
RF	Radio frequency
RMS	Root mean square

SBS	Stimulated Brillouin scattering
SESAM	Semiconductor saturable absorber mirror
SHE	Swift-Hohenberg equation
SMF	Single-mode fiber
SNR	Signal-to-noise ratio
SPM	Self phase modulation
SSF	Split-step Fourier
TB	Time-bandwidth
WDM	Wavelength-division multiplexing
YDF	Ytterbium doped fiber
Yb-DCF	Ytterbium doped double cladding fiber

1 Introduction

1.1. BACKGROUND

Mode-locking of a laser refers to a locking of the phase relations between many neighboring longitudinal modes of the laser cavity. Locking of such phase relations enables a periodic variation in the laser output which is stable over time, and with a periodicity given by round trip time of the cavity. If sufficient longitudinal modes are locked together with no phase difference, they result in a short pulse which may have a significantly high peak power and short pulse width [1, 2] .

Mode-locking now is a routine technique to generate ultra-short optical pulse with pulse width around or below ps [3-9]. Ultra-fast optics have been a rich research field for decades, and today short pulsed laser systems find numerous applications in areas of fundamental research such as for medical and industrial applications. For example, ultra-fast laser systems are used for time resolved studies in chemistry, optical frequency metrology, terahertz generation, two photon spectroscopy and microscopy, and optical coherence tomography [10-16]. Other medical related applications are eye laser surgery and dentist drills [17, 18]. In the industry, ultra-fast

lasers are used for micro-machining and marking [19]. The corner stone of ultra-fast optics is the mode-locked laser, and developments of mode-locked lasers have been a huge research field itself. Various mechanisms (both active and passive) exist for mode-locking lasers. Conventionally, active mode-locking can generate optical pulse train with high repetition rate and is attractive in optical communications [20]. For passive mode-locking, it generates the shortest optical pulse ($\sim$ fs) and extremely high peak power which can't be achieved in the actively mode-locked laser [3, 5, 9].

Laser can be classified into solid state laser, gas laser, dye laser and diode laser according to the laser medium. Solid state laser is preferred in terms of reliability and long term stability [21-23]. However, solid-state lasers require stable laboratory-like environments with optical tables and stabilized room temperature. Furthermore, solid-state lasers have high power consumption, and often require maintenance. Gas lasers also suffer from these drawbacks.

With the development of semiconductor industry, diode lasers are now commonly used. Diode lasers have advantages of very compact size, low cost and high power efficiency. As diode lasers can be pumped by electric power, they are widely used in commercial product such as laser printers, CD/DVD players and laser pointers. As the output power of diode lasers has been significantly increased in the last decades, diode lasers can also be used to pump other lasers or even in cutting and welding. At present, the emitting range of diode lasers cover the optical communication windows and diode lasers are widely used in fiber communication systems. The main issues of diode laser are the low beam quality and the sensitivity to the temperature.

After the rare-earth doped fiber was invented, fiber based lasers were developed

and soon became very attractive [24, 25]. The potential of making compact, robust laser systems with low power consumption at relative low price make fiber lasers a very promising alternative to classical solid state lasers. The key properties that make rare-earth doped fiber attractive as laser gain media are the high single pass gain combined with broad gain bandwidths and excellent beam quality. A major reason for the recent development of fiber lasers is that fiber lasers can now be directly pumped by laser diodes. Combined with the huge progress and technological development of high power diode lasers, fiber lasers are competitive supplements for classical solid state lasers.

1.2. MOTIVATIONS

Passively mode-locked fiber lasers with ultra-short optical pulse output have been intensively investigated as a research area in the past decade. Within the past few years, there have been a growing number of applications of such lasers. Researcher's interests have been attracted by generating optical pulses with more critical parameters which would benefit a wider application area of passively mode-locked fiber lasers. For example, multiple wavelength emission of passively mode-locked fiber laser has been studied both theoretically and experimentally to improve the performance of fiber laser in optical fiber communications [26]; mode-locking in different wavelength range have been reported to explore the applications in micro-machining, sensing or light detection and ranging (LIDAR) system [27-29]; new laser cavity design have been demonstrated to increase the output pulse energy [5, 28, 30-33]. Passively mode-locked fiber lasers offer a more compact, cheaper, and in some cases more stable solution than the corresponding bulky laser.

Although numerous investigations have been carried on passively mode-locked fiber lasers, there are still challenges for improving the performance of the laser. Due to the nonlinearity of optical fiber, the complex nonlinear mechanism impedes researchers to give a detail, accurate, analytical view to such lasers [34]. Therefore, there are a lot of theoretical works to be done to investigate the dynamics of the passively mode-locked fiber lasers.

Other than theoretical interests, experimental research on passively mode-locked fiber lasers to generate mode-locked pulse with critical parameters is also attractive. Conventionally, passively mode-locked fiber lasers generate optical pulse with fs-ps pulse width, 10~100MHz repetition rate and less than 1 nJ pulse energy [35-37]. Such characteristics limit the application range of the passively mode-locked fiber lasers. For example, in micro-machining system, a much lower repetition rate is needed and much higher pulse energy is required. To optimize the fiber laser for various applications is of strong merit.

1.3. OBJECTIVES

Conventionally, the pulse shaping in passively mode-locked lasers was thought to be dominated by the balancing between the fiber nonlinearity and dispersion [3, 4, 38-40]. The concept of “soliton” in optical fiber was used to describe the behavior of the mode-locked pulses [20, 41, 42]. The optical soliton is a stable solution of the nonlinear Schrödinger equation (NLSE) which describes the Hamilton system with Kerr nonlinearity and second order dispersion. A soliton can be obtained in optical fiber with anomalous dispersion or in fiber line with a dispersion map [43]. To achieve such solitons, the net gain and loss of the laser cavity must be minimized to

guarantee the Hamilton nature of the system. In this mean, the passively mode-locked fiber lasers were also known as solitons laser or dispersion managed soliton lasers.

With the development of the ultra-fast optics field, ultra-short optical pulses with high pulse energy are required. The conventional soliton laser can only generate $\sim$ pJ pulse energy which is not adequate for such applications. Recently, passive mode-locking in fiber lasers with normal net dispersion has been demonstrated. Such lasers can generate high pulse energy ($\sim$ nJ) and sustain high cavity loss [32, 44-47]. Other than the soliton mechanism, the dissipative process of gain-loss dominates the pulse shaping and stabilizing [48-54]. Therefore, the conventional theory on passively mode-locked fiber lasers becomes insufficient. The investigation on the dissipative process is not only important for fundamental research, but also valuable for practical applications.

The dissipative mechanism in a passively mode-locked fiber laser is mainly provided by the gain, the nonlinear loss of the saturation absorber and the spectral filtering effect in the laser cavity. The main objective of this thesis is to analyze the effect of the dissipative process on pulse shaping in passively mode-locked fiber laser. The aims of this thesis are to give a better understanding of the dissipative pulse shaping mechanism of the passively mode-locked fiber lasers and investigate the optimization of the laser design for practical applications.

1.4. ORIGINAL CONTRIBUTIONS

The original contributions of this thesis are as follow:

- Investigate and demonstrate the effect of the properties of the saturable absorber on pulse shaping in a dispersion managed laser
- Demonstrate noise-like pulses with 28 nJ pulse energy by correctly setting the properties of the saturable absorber
- Demonstrate a dual-wavelength passively mode-locked fiber laser by incorporating polarization maintaining fiber (PMF) into the laser cavity.
- Investigate the mechanism of multiple-pulsing in a passively mode-locked fiber laser with all-normal-dispersion cavity and confirm the pulse energy clamping mechanism caused by spectral filter is the key factor for multiple pulsing.
- Demonstrate an analytical method to investigate the multiple-pulsing induced bandwidth limitation of the all-normal dispersion passively mode-locked fiber laser (ANDi-laser), and find that mode-locked pulse with broader bandwidth can be achieved by increasing the modulation depth of the saturable absorber.
- Optimize the laser design according to the net dispersion and the modulation depth of the saturable absorber. High energy pulse with broad bandwidth has been achieved.
- Demonstrate wavelength switching in an erbium doped fiber (EDF) laser mode-locked by NPR.

- Propose and demonstrate a high energy ANDi-laser with ultra-low repetition rate. The pulse shaping mechanism is mainly provided by a semiconductor saturable absorber (SESAM)
- Demonstrate an all-fiber mode-locked laser system with ultra-low repetition rate, more than 4 μJ pulse energy has been achieved.

1.5. OUTLINE

The thesis is organized as follow:

Chapter 1 gives a brief introduction to the research work of this thesis.

Chapter 2 introduces the fundamental principles of the laser and the passively mode-locked fiber lasers.

Chapter 3 analyzes the pulse shaping mechanism of the passively mode-locked fiber lasers, and demonstrates a numerical model to investigate the dynamics of the laser. Mode-locking according to different pulse shaping mechanism have been demonstrated and characterized.

Chapter 4 investigates the function of the saturable absorber in a dispersion managed passively mode-locked fiber laser with normal net dispersion. It shows that the saturable absorber can affect pulse shaping mechanism and results in different operation states in the passively mode-locked fiber laser.

Chapter 5 analyzes the mechanism of limitation of the pulse energy and the pulse bandwidth in a passively mode-locked fiber laser with all-normal-dispersion fiber cavity. It shows that the pulse energy and the pulse bandwidth can be optimized

by correctly setting the modulation depth of the saturable absorber and the net dispersion. A 5.3 nJ mode-locked pulse with 15 nm bandwidth in an erbium doped fiber laser has been achieved. As the gain-filtering effect of the erbium doped fiber (EDF) is important for pulse shaping in the laser, the dual-peak gain profile of the EDF in the laser is investigated and a wavelength switching effect is observed.

Chapter 6 demonstrates an ultra-low repetition rate, high energy mode-locked fiber laser. In this case, the mode-locked pulse is mainly shaped by the saturable absorber. The laser is mode-locked by a SESAM. The laser can only be stably mode-locked with ultra-long laser cavity and can generate pulse train with repetition rate as low as 187 kHz. The mechanism of mode-locking with ultra-long laser cavity is analyzed. It shows that the saturable absorber can act as a spectral filter for extremely chirped optical pulse and shape the pulse spectrum.

Chapter 7 gives the conclusions of the research works and the recommendation for future work.

2 Fundamental Laser Theory

2.1. INTRODUCTION

The name LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The possibility of constructing a laser using “stimulated emission” was predicted by Albert Einstein as early as 1917. Almost 40 years after the theory was proposed, the first laser was demonstrated as a gas laser by Theodore Maiman [55]. Comparing with other light source, the laser has the unique properties of excellent directionality, high intensity and long coherence length.

Mode-locked lasers can be traced to Lamb’s work in which he investigated the frequency locking of three modes [56]. In 1964, DiDomenico theoretically predicted mode-locking [57]. In the same year, Hargrove *et al* demonstrated the first mode-locked laser [58]. Stabilization of amplitude and frequency of the modes in a He-Ne laser was achieved by internally modulating the laser with an acoustic-optical modulator. 56 MHz repetition rate pulses with 2.5 ns pulse width were observed.

Passive mode-locking was firstly observed in a Q-switched laser in 1965 [59]. Mocker and Collins observed that the Q-switched pulse could split into mode-locked

pulses in a ruby laser. However, the mode-locking was unstable. The first stable passively mode-locked laser was demonstrated by Ippen, Shank and Dienes in 1972. They achieved 1.5 ps stable pulse train in a dye laser [60].

The first fiber laser was demonstrated in 1963 [61], by Koester and Snitzer . A Nd-doped glass fiber was used as the gain medium and laser output at 1061nm was achieved. However, the first mode-locked fiber laser was not reported until 1984, over 20 years after the first fiber laser. The first soliton laser was demonstrated one year later by Mollenauer and Stolen [62]. After that, passively mode-locked fiber lasers attracted intensive investigations. By now, the passively mode-locked fiber laser has been developed for different applications. Mode-locked pulses with ultra-low jitter, ultra-short pulse width, high pulse energy has been achieved in passively mode-locked fiber lasers according to different cavity designs [63-65].

2.2. PRINCIPLE OF THE LASER

A typical laser includes two essential parts: the gain medium and the optical resonator, as shown in Figure 2.1.

Figure 2.1 Schematic of a laser setup; M1: Mirror 1; M2: Partial transmission mirror

The gain medium of the laser is a material which provides optical amplification by the process of stimulated emission. When the gain medium is pumped, some of the electrons absorb the pump energy and are excited to a higher energy level [66]. Figure 2.2 shows the process of the emission.

Figure 2.2 Schematic of the laser emission process in a (a) three-level system
(b) four level system

The excited atom can re-emit this excitation energy by emitting a photon, either spontaneously or stimulated. The emitted photon energy can be written as [66]:

$$E_p = h\nu = \Delta E \quad (2.1)$$

where E_p is the energy of the emitted photon, h is the Plank constant, ν is the frequency of the photon. ΔE is the energy gap between the two energy levels. The emitted photon in stimulated emission has the same phase, wavelength and direction with the incident photon, thus resulting in optical amplification.

Due to the broadening effect, energy levels in an atomic system are of a finite width and the gain medium can always provide optical amplification over certain bandwidth, as shown in Figure 2.3.

Figure 2.3 The gain profile with a Lorentzian lineshape

Besides the gain medium, an optical resonator is required to provide strong feedback to the laser. In the simplest case, the resonator consists of two mirrors facing each other, surrounding the gain medium of the laser. Since light is a wave, when bouncing between the mirrors of the cavity the light will constructively and destructively interfere with itself, leading to the formation of standing waves between the mirrors.

Figure 2.4 Longitudinal modes in a laser cavity

These standing waves form a discrete set of frequencies, as shown in Figure 2.4, known as the longitudinal modes of the cavity. These modes are the only frequencies of light which can be self-regenerating and allowed to oscillate by the resonant cavity. All the other frequencies of light are suppressed by destructive interference. For a

simple plane-mirror cavity, the allowed modes are those for which the separation distance of the mirrors L is an exact multiple of half the wavelength of the light λ , thus

$$2L = q\lambda \quad (2.2)$$

where q is an integer known as the mode order.

In practice, the separation distance of the mirrors L is usually much greater than the wavelength of light λ , so the relevant values of q are large. The frequency separation between any two adjacent modes q and $q+1$ is a fixed value:

$$\Delta f = c / 2L \quad (2.3)$$

where c is the speed of light ($\approx 3 \times 10^8$ m/s).

The bandwidth of the gain medium and the optical resonator decide the range of the emitting frequency of a laser, as shown in Figure 2.5.

Figure 2.5 The emission frequencies of a laser

2.3. PRINCIPLE OF MODE-LOCKING

Each individual longitudinal mode has a certain bandwidth or narrow range of frequencies over which it operates. This bandwidth is mainly determined by the finesse of the cavity and it is always much smaller than the inter-mode frequency

separation. Therefore, it is reasonable to treat them as ideal plane wave as described in equation (2.4).

$$E_j(t) = E_j \exp[i(\omega_j t + \phi_j)] \quad (2.4)$$

where E_j is the amplitude of electrical field, ω_j is the frequency, ϕ_j is the phase of the j^{th} longitudinal mode, respectively. Normally, although the frequencies of the longitudinal modes are fixed by the optical resonator, the phase of the modes are randomly arranged. Considering an ideal case that all the longitudinal modes have the same amplitude E_0 , the output power of the laser is:

$$I(t) = |E(t)|^2 = E_0^2 \left| \sum_{j=0}^{N-1} \exp(i\omega_j t) \exp(i\phi_j) \right|^2 \quad (2.5)$$

The output power randomly varies due to the random phase of different longitudinal modes.

However, when the phase of the multiple longitudinal modes are the same, the output power of the laser becomes:

$$\begin{aligned} I(t) &= |E(t)|^2 = E_0^2 \left| \sum_{j=0}^{N-1} \exp(i\omega_j t) \exp(i\phi_j) \right|^2 \\ &= E_0^2 |\exp(i\phi)|^2 \left| \sum_{j=0}^{N-1} \exp(i\omega_j t) \right|^2 \\ &= E_0^2 \left| \sum_{j=0}^{N-1} \exp(i\omega_j t) \right|^2 \\ &= E_0^2 \frac{\sin^2(N\Delta\omega t / 2)}{\sin^2(\Delta\omega t / 2)} \end{aligned} \quad (2.6)$$

where $\Delta\omega = 2\pi\Delta f$ is the frequency difference between two neighboring longitudinal modes, N is the number of the longitudinal modes. In this case, the laser output is an optical pulse train with:

- Repetition rate equal to Δf , and the pulse period $T = 1/\Delta\nu$, where $\Delta\nu$ is the full width of the gain band.
- Pulse peak power equals to NE_0^2
- Pulse width $\tau = T/N$, where $T = 1/\Delta f$

The technique which is used to lock the phase of the longitudinal modes in a laser is called “mode-locking”. As shown above, when the laser is mode-locked, the laser output short optical pulse train with fixed period. The more the longitudinal modes number, the higher the pulse peak power and the narrower the pulse width.

In a real laser, the amplitudes of different longitudinal modes are not equal. The amplitude is dominant by the gain profile of the gain medium, as shown in Figure 2.5. As a good approximation, the gain profile can be treated as a Gaussian function, therefore, the output power of the laser becomes

$$I(t) = |E(t)|^2 = \left| \sum_{j=0}^{N-1} E_j \exp(i\omega_j t) \right|^2 \quad (2.7)$$

$$\sim \exp\left[-\ln 2 \left(\frac{2t}{\Delta t}\right)^2\right]$$

The full width of the half maximum (FWHM) of the pulse is $\Delta t = \frac{2 \ln 2}{\pi \Delta \nu} = \frac{0.441}{\Delta \nu}$,

and the time-bandwidth (TB) product is $\Delta t \Delta \nu = 0.441$. The TB product is the result obtained by multiplying the system bandwidth by the pulse duration, it is always used

to evaluate the pulse quality in a mode-locked laser. The value of the TB product is decided by two factors: the pulse chirp and the pulse shape. When the phase of each longitudinal mode is perfectly matched, the pulse is transform limited and the TB product has the minimum value. The TB product of a transform limited pulse also depends on the pulse profile. For example, the TB product of a transform limited Gaussian pulse is 0.441, and the TB product of a transform limited hyperbolic secant pulse is 0.315. When the pulse is chirped, which means there is phase shift between the modes, the TB product will increase and the pulse is no longer transform limited. Normally, transform limited pulse with minimum TB product is preferred to achieve shortest pulse width with certain bandwidth.

A periodic modulation on the laser cavity can be an effective method to achieve mode-locking [67]. For example, considering this in the frequency domain, if a mode has optical frequency ν , and is amplitude-modulated at a frequency f , the resulting signal has sidebands at optical frequencies $\nu-f$ and $\nu+f$ which have the same phase to the original frequency. When the modulation frequency f equals to the integral times of fundamental frequency of the laser cavity, $f = n\Delta f$, the sidebands are located at the n^{th} neighbor longitudinal modes and can oscillate in the laser cavity. Therefore, the longitudinal modes are locked to the same phase and enable mode-locking for short pulses. When $n=1$, the laser is mode-locked at the fundamental frequency. When $n>1$, the repetition rate of the mode-locked pulses is n times of the fundamental frequency Δf and results in harmonic mode-locking.

2.4. MODE-LOCKING TECHNIQUES

Active mode-locking

In general, there are two main types of mode-locking mechanisms: active mode-locking and passive mode-locking. In active mode-locking, a modulator modulated by an external signal source must be applied. The modulator can be either an amplitude modulator (AM) or a phase modulator (FM) [68, 69]. When the modulation frequency is the integral times of the laser cavity frequency, the laser can be mode-locked and output pulse train is synchronized to the external modulation signal. By using harmonic active mode-locking, the repetition rate can be over 1000 times of the fundamental laser frequency and as high as tens of GHz. A bandpass filter (BPF) is always required to stabilize the output. Figure 2.6 shows a typical actively mode-locked fiber laser.

Figure 2.6 Schematic of an actively mode-locked fiber laser

Due to the high repetition rate and the high pulse quality, actively mode-locked lasers can be excellent pulse sources for high bit rate optical communication systems.

However, the pulse width is always over ps and the pulse peak power is typically below 1 W.

Passive mode-locking

Unlike active mode-locking, passive mode-locking doesn't require any external signal source [60].

In the passively mode-locked laser, a saturable absorber must be inserted in the laser cavity to start the mode-locking, as shown in Figure 2.7. The saturable absorber is an optical device that exhibits an intensity-dependent transmission [70]. The device behaves differently depending on the intensity of the light passing through it. For passive mode-locking, ideally a saturable absorber will selectively absorb low-intensity light, and transmit light which is of sufficiently high intensity, as shown in Figure 2.8. Such mechanism provides the so called "positive feedback" to the laser cavity which induces higher transmission to light with higher intensity.

Figure 2.7 Schematic of a passively mode-locked laser; M1: Mirror I; M2:

Partial transmission mirror; SA: saturable absorber

Figure 2.8 The function of an ideal saturable absorber

When placed in a laser cavity, a saturable absorber will attenuate low-intensity constant wave light (pulse wings). Because of the random intensity fluctuations experienced by an un-modelocked laser, a random intense spike will be transmitted preferentially by the saturable absorber. As the light in the cavity oscillates, this process repeats, leads to selective amplification of the high-intensity spikes, and absorption of the low-intensity light. After many round trips, this effect builds up a train of pulses and starts the mode-locking of the laser.

The passive mode-locking can also be understood from the frequency domain. The saturable absorber modulates the light in each roundtrip of the laser cavity with a period of roundtrip time. The modulation frequency equals to the fundamental frequency of the laser and generates mode-locked pulse train with fundamental repetition rate. Mode-locking based on saturable absorption has the advantage of self-starting and self-sustaining for properly designed laser cavities without any external signal reference.

The repetition rate of passively mode-locked fiber laser is much lower (typically 10~100 MHz) compared to actively mode-locked fiber laser due to the long laser cavity and the low fundamental frequency. Although harmonic mode-locking can be

employed to increase the repetition rate, it always reduces the stability of the laser and increases the noise [71]. Therefore, the passively mode-locked fiber laser is not a good choice for the source of high bit-rate data transmission systems.

However, the peak power of the pulses from passively mode-locked lasers can be much higher than that from actively mode-locked fiber lasers. Over 1 kW peak power can be easily achieved and it can be boosted to over 1 MW after amplification [72, 73]. The pulse width is also much shorter. Such high peak power ultra-short pulse train is very attractive in nonlinear optics research, all-optical logic gate, laser drilling and machining.

2.5. SATURABLE ABSORBER

Numerous mechanisms can act as saturable absorber. Semiconductor materials in the forms of quantum wells or quantum dots can provide saturable absorption in a certain bandwidth [7, 74, 75]. Other methods based on fast artificial saturable absorption include Kerr-lens mode-locking, nonlinear polarization rotation (NPR) and self-phase modulation (SPM) in nonlinear loop mirrors (NOLMs) [76-82]. The most widely used saturable absorbers for fiber lasers are the SESAM and the NPR.

Semiconductor saturable absorber mirror

A SESAM consists of a Bragg-mirror on a semiconductor wafer, such as GaAs, incorporating materials with an intensity dependent absorption. The saturable absorber layer consists of a semiconductor material with a direct band gap slightly lower than the photon energy. Normally GaAs/AlAs is used for the Bragg mirrors and InGaAs Quantum Wells for the saturable absorber material. During the absorption

electron-hole pairs are created in the film. As the number of photons increases, more electrons are excited, but as only a finite number of electron-hole pairs can be created, the absorption saturates. The electron-hole pairs recombined non-radiatively, and after a certain period of time again ready to absorb photons.

Figure 2.9 Schematic of a SESAM based passively mode-locked fiber laser with a linear cavity. OC: Optical coupler; WDM: Wavelength division multiplexing coupler.

The recovery time should ideally be as small as possible. Recovery times of the same order of magnitude as the pulse duration will cause asymmetric spectra if the pulse is chirped, and hence strongly affect the pulse dynamics inside the cavity [83]. Larger recovery times can limit the obtainable pulse width from the laser. Because the relaxation time due to the spontaneous photon emission in a semiconductor is about 1 ns, some precautions have to be taken to shorten it drastically. Two technologies are used to introduce lattice defects in the absorber layer for fast non-radiative relaxation of the carriers: low-temperature molecular beam epitaxy (LT-MBE) and ion implantation. The relaxation time can be adjusted by adjusting the growth temperature in case of LT-MBE and the ion dose in case of ion implantation. SESAMs have been known to exhibit a bi-temporal recovery time with the shortest time in the ps or sub-ps range. A bi-temporal recovery time is ideal for mode-locked lasers, because the short recovery time enables short pulses and the longer recovery time is needed to

initiate mode-locking. Figure 2.9 gives a typical SESAM based passively mode-locked fiber laser with a linear laser cavity.

The SESAM has already been used in commercialized passively mode-locked fiber lasers. The advantage of SESAM is that it can provide stable modulation depth and saturation energy. This characteristic is very attractive for commercial applications due to its reliability and robustness. However, the semiconductor properties can lead to low damage threshold of the SESAM, and the peak power in the laser cavity is limited.

Nonlinear polarization rotation

Figure 2.10 Principle of the NPR mode-locking

One widely used artificial saturable absorber is to use NPR technique by inserting a polarizer into the laser cavity. By correct controlling the polarization state in a fiber with polarization controllers (PCs), the polarizer can provide intensity dependent loss. The principle is demonstrated in Figure 2.10. An optical pulse passing through a polarizer is linear polarized. After one roundtrip in the laser cavity, the fiber

nonlinearity will induce NPR effect and the polarization state of the pulse becomes intensity dependent. The polarization state is non-uniformly distributed along the pulse in time domain. By proper setting of the PCs in the laser cavity, the pulse peak can achieve highest transmission and the pulse wings which have lower intensity and therefore a different polarization state will be suppressed. In this way, an artificial saturable absorber is formed. Since the saturable absorption effect comes from the Kerr nonlinear effect, the NPR has ultra-fast response time, and it can always be treated as a device responses instantaneously to the pulse intensity and results in additive pulse limiting (APL) mode-locking [84].

Compared to SESAM, the NPR mode-locking can provide variable modulation depth and saturation energy. Hence, the NPR technique is widely used to investigate the pulse dynamics under different mode-locking conditions. It can also support much higher peak power in the laser cavity without physical damage.

Figure 2.11 shows the schematic of a typical fiber laser mode-locked by NPR.

Figure 2.11 Schematic of a NPR mode-locked fiber laser with a ring cavity;

PBS: Polarization beam splitter; PC: polarization controller

The drawback of the NPR technique is that it is very sensitive to the polarization state, and variation of the environment may cause unstable of mode-locking. This can be impact of the commercial applications of NPR.

2.6. CHARACTERIZATION TECHNIQUES

The most frequently concerned parameters of the passively mode-locked fiber lasers are listed below:

- Pulse width
- Optical spectrum
- Repetition rate
- Pulse energy
- Noise

Pulse width

For mode-locked pulse with pulse width >10 ps, the pulse width can be monitored by a high speed photodetector and an oscilloscope. When the pulse width is much shorter than 10 ps, the pulse width cannot be easily measured by optoelectronic methods, since the response time of photodiodes and oscilloscopes are normally larger than a few ps. In this case an optical autocorrelator shall be employed. The autocorrelator measures the autocorrelation trace $G(\tau)$ of the pulse intensity $I(t)$:

$$G(\tau) = \int_{-\infty}^{\infty} I(t)I(t-\tau)dt \quad (2.8)$$

It can be shown that the intensity autocorrelation width of a pulse is related to the intensity width. For a Gaussian time profile, the autocorrelation width is $\sqrt{2}$ times

longer than the width of the intensity, and it is 1.54 times longer in the case of a hyperbolic secant squared pulse. This numerical factor, which depends on the shape of the pulse, is called the de-convolution factor. If this factor is known, or assumed, the pulse width can be measured using an intensity autocorrelation. The resolution of the optical autocorrelator can be a few fs and it can be used to measure the ultra-short pulses with < 1 ps pulse width.

Optical spectrum

The output optical spectrum of the passively mode-locked fiber laser is of special importance because it reveals the information of the pulse shaping mechanism. At present, the commercial diffraction grating optical spectrum analyzer (OSA) can covers a wide wavelength range and has a high resolution of 0.01 nm, and provide accurate enough monitoring on the laser spectrum. Pulse bandwidth can be achieved from the spectrum and the TB bandwidth can be calculated with the information of pulse width.

Repetition rate, pulse energy and noise

The repetition rate of the mode-locked pulse can be measured by measuring the pulse interval on an oscilloscope. It can also be accurately measured by a radio-frequency (RF) spectrum analyzer.

As there is no direct measuring method for the pulse energy, the pulse energy is always achieved from the average power of the laser P_{ave} and the pulse repetition rate

f_{rep} :

$$E_p = P_{ave} / f_{rep} \quad (2.9)$$

In passively mode-locked fiber lasers, normally the continuous wave (CW) emission of the laser is suppressed by the saturable absorber, and the mode-locked pulse is the main contribution of the output power and the equation (2.9) can provide enough accuracy for pulse energy evaluation.

The RF spectrum of the mode-locked pulse can also be used to measure the noise of the mode-locked pulse. By using the Von der Linde method, the intensity noise and the phase noise of the pulse train can be achieved respectively from the RF spectrum at different harmonic orders [85].

2.7. SUMMARY

In this chapter, the mechanism of mode-locking is reviewed. Active and passive mode-locking techniques are briefly introduced. To give a clear view to passive mode-locking in fiber lasers, some typical approaches to saturable absorbers are demonstrated, such as the SESAM and the NPR technique. Each approach has different influence to the mode-locked pulse. The mode-locking scheme must be carefully chosen according to the objective. Finally, the parameters and the techniques used to evaluate the performance of the passively mode-locked fiber laser are introduced.

3 Pulse Shaping in Passively Mode-Locked Fiber Lasers

3.1. INTRODUCTION

Pulse shaping in mode-locked lasers has been widely investigated. For classical solid state and dye lasers advanced analytical theories exist, and the master equation developed by Haus can be used to describe many types of mode-locked laser [86, 87]. However, for passively mode-locked fiber lasers, the theory is only adequate if the effects of all cavity elements on the pulse are weak on each pass. As the nonlinearity and the dispersion are strong in fiber lasers, a more practical model for pulse shaping is required.

Figure 3.1 shows the pulse shaping effects of the essential elements in a passively mode-locked fiber laser. In an optical fiber oscillator, the fiber dispersion and nonlinearity affect pulse shape in both the temporal domain and the frequency domain, thus producing strong pulse shaping mechanism. The gain medium in a fiber laser is always rare earth doped fiber pumped by a laser diode through a wavelength division multiplexing (WDM) coupler. The gain saturation and the gain dispersion

affect the pulse evolution together with the nonlinearity and the dispersion. Moreover, gain saturation is a key factor for self-start mode-locking [88, 89]. The saturable absorber is used to mode-lock the laser and provides a pulse shortening effect. The net loss of the laser caused by the output coupler(s) and fiber connection induces strong gain-loss modulation to the pulse together with the net gain. To theoretically investigate the passively mode-locked fiber laser, each part of the laser must be correctly modeled.

Figure 3.1 Pulse shaping of the essential devices in a passively mode-locked fiber laser

In this chapter, a numerical model for the passively mode-locked fiber laser is given. Mode-locked pulses according to different pulse shaping mechanism are demonstrated.

3.2. NUMERICAL MODEL ON PASSIVELY MODE LOCKED FIBER LASER

Pulse propagation in optical fiber

To accurately model the light interaction with medium such as optical fiber, the most basic mathematical method is via Maxwell field theory. With this tool, many systems involving light can in principle be modeled exactly. However, the complexity of the system is often a limiting factor and approximations have to be introduced to obtain either simpler analytical equations or numerical results. The most important approximations used to model the pulse propagation in optical fiber are the non-resonance approximation, the slowly varying envelop approximation and the weak wave-guiding approximation [90]. The Maxwell equations then reduce to a pulse propagation equation which is well known as nonlinear Schrödinger equation (NLSE), as shown in equation (3.1).

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A \quad (3.1)$$

where $\tilde{A}$ is a slowly varying function of z which describe the electrical amplitude of the optical pulse, β_2 is the chromatic dispersion, γ is the nonlinear coefficient of the fiber and α is the attenuation factor of the fiber. At present, optical fiber can be fabricated with extremely low loss which can be neglected without affect the calculation. Then the equation becomes:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} = i\gamma |A|^2 A \quad (3.2)$$

To evaluate the effect of dispersion and nonlinearity on pulse evolution, the dispersion length and the nonlinear length is defined as:

$$L_D = \left| \frac{T_0^2}{\beta_2} \right| \quad (3.3)$$

$$L_{NL} = \frac{1}{\gamma P_0} \quad (3.4)$$

where T_0 is the pulse width, and P_0 is the pulse peak power. When the propagation distance is over L_D or L_{NL} , the dispersive effect or the nonlinear effect becomes important.

When the dispersion of optical fiber is anomalous in which $\beta_2 < 0$, a stable pulse solution for the NLSE can be found analytically, which is known as optical “soliton”:

$$A(z, T) = T_0 \sqrt{\frac{|\beta_2|}{\gamma}} \operatorname{sech} \left(\frac{T}{T_0} \right) \exp \left(\frac{i|\beta_2|z}{2T_0^2} \right) \quad (3.5)$$

The phase changes uniformly along the pulse while the pulse is propagating in the optical fiber, and the pulse profile doesn't change in both time domain and frequency domain. In this case, $L_D = L_{NL}$, and the soliton is formed as a result of balancing between the effect of the chromatic dispersion and the self-phase modulation (SPM).

In passively mode-locked fiber lasers, there are always components other than optical fiber such as optical amplifier, saturable absorber, output coupler, etc. Actually, passively mode-locked fiber lasers are dissipative system which includes optical gain and loss process. By this mean, an output pulse is a stable state of this dissipative system, and it is also known as dissipative soliton.

Due to the effect of the other components, the stable pulse profile no longer follows equation (3.5). In this case, the NLSE can't be solved analytically and numerical method must be employed to investigate the pulse propagation in optical fibers.

Normally, the NLSE can be solved numerically by time domain finite difference method or the split-step Fourier (SSF) method which is a pseudo-spectral method [91]. Compared to the finite difference method, the SSF method has the advantage of much faster. Although it can not account for forward and backward propagating waves, it works well in modeling ring lasers in which the backward propagating wave is eliminated.

Fiber amplifier

In fiber lasers, the gain can be provided by doping the fiber with appropriate optical active atoms, like rare earth atoms (Erbium, Ytterbium, Thulium, Neodymium, etc.), and by creating a population inversion by means of optical pumping.

By using rate equations, the gain coefficient of the doped fiber can be calculated as [90]:

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2 + E / E_p} \quad (3.6)$$

where g_0 is the peak gain value, ω is the frequency of the incident signal, ω_0 is the central gain frequency, E is the incident pulse energy, E_p is the saturation energy of the rare-earth-doped fiber and depends on dopant parameters, T_2 is the dipole relaxation time and is typically small (~ 100 fs) for fiber amplifiers.

Equation (3.6) reveals that the gain of a pulse depends on the ratio of the pulse energy over the saturation energy. The gain saturates while this ratio increases. The saturation energy of the gain fiber is usually around $1\mu\text{J}$ which is usually much larger than the pulse energy, and the saturation effect is almost negligible for a single pulse. However, as the pulse duration as well as the round trip time is usually much shorter than the relaxation time of the excited states in the rare earth atoms, the population inversion in steady state operation actually can be saturated by the pulse train. The lifetime of the excited state is around 10 ms in erbium and around 1 ms in ytterbium, and the typical pulse interval is around 10~100 ns. Strong saturation effects can be generated by the thousands of pulses propagating through the gain fiber within the excited states life time. Therefore, the saturation energy for each single pulse is much lower. It is reasonable to set the saturation energy of the gain fiber to be 1 nJ for a single pulse when modeling a passively mode-locked fiber laser.

By only considering gain with small incident signal, the ratio E/E_p can be neglected in equation (3.6), and the gain coefficient then becomes:

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)T_2^2} \quad (3.7)$$

where T_2 is life time of the excited states and g is the saturated gain of the fiber. It shows that the gain decreases when the incident frequency deviates from the central gain frequency. The gain spectrum can be approximated to have a Lorentzian profile which is characteristic of homogeneously broadened systems. Hence the gain fiber can form spectral filtering effect by providing wavelength dependent gain.

If the fiber is pumped from one end, this further creates a non-uniform distribution of population inversion in the fiber due to the gradual absorption of the

pump light. It results in a non-uniform gain for pulse propagating in it. This non-uniform population inversion can be calculated using rate equations for the average power distribution in the fiber. However, to simplify the numerical model and reduce computation time, this z dependence can be neglected if the doped fiber is short. Hence the gain can be treated as a constant along the gain fiber.

The equation of pulse propagation in a gain fiber is governed by the Ginzburg-Landau equation (GLE) [90].

$$\frac{\partial A}{\partial z} + \frac{i}{2}(\beta_2 + igT_2^2) \frac{\partial^2 A}{\partial T^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A + \frac{1}{2}(g - \alpha)A \quad (3.8)$$

where T_2 is the life time of the excited states where T_2 is the life time of the excited states and g is the saturated gain of the fiber

$$g = g_0 \frac{1}{1 + \frac{E_{pulse}}{E_{sat}}} \quad (3.9)$$

where g_0 is the small signal gain of the gain fiber which is treated as a constant along the fiber, E_{pulse} is the energy of a single pulse and E_{sat} is saturation energy of the gain fiber for a single pulse.

By transferring T_2 into the frequency domain, (3.8) can be written as

$$\frac{\partial A}{\partial z} + \frac{i}{2}(\beta_2 + i \frac{g}{\Omega_g^2}) \frac{\partial^2 A}{\partial T^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A + \frac{1}{2}(g - \alpha)A \quad (3.10)$$

where $\Omega_g^2 = \frac{1}{T_2^2}$ is the gain bandwidth.

Saturable absorber

The saturable absorber is the key components for self-start mode-locking. It can

also provide pulse-shortening effect due to the intensity dependent loss. The transmission property of a saturable absorber with a finite recovery time can be modeled as [83]:

$$\frac{\partial l_s}{\partial t} = -\frac{l_s - l_0}{T_{rec}} - \frac{P(t)}{E_{sat}^{SA}} l_s \quad (3.11)$$

where T_{rec} is the absorption recovery time, l_s is the saturation absorption of the absorber, l_0 is the initial absorption of the absorber, $P(t)$ is the temporal power of the pulse and E_{sat}^{SA} is saturation energy of the saturable absorber.

For saturable absorbers with recovery times much faster than the pulse duration, the loss can be modeled as [83]:

$$l_s = \frac{l_0}{[1 + P(t) / P_{sat}]} \quad (3.12)$$

where P_{sat} is the saturation power of the absorber.

Simulation model

By proper modeling of all the constituent devices, a model of the passively mode-locked fiber laser can be obtained by combining all the devices in the correct order, as shown in Figure 3.2. The order of each device can be varied according to different cavity design. The numerical simulation starts with an initially noisy pulse, and applies the effect of each element of the laser once at a time. After every round trip, the sequence is simply repeated until the pulse has converged to a stable solution, which will be the stably mode-locked pulse.

Figure 3.2 Schematic of the numerical model; l_L is the linear loss of the laser cavity

To determine if the pulse has reached the steady state is that the pulse should reproduce itself with a phase shift after every round trip. To check if this requirement is reached, it is efficient to monitor the root-mean-square (RMS) temporal duration, the RMS spectral width, the mean central wavelength and the pulse energy. If all these parameters reach a stable value, the pulse can be treated as a stable mode-locked pulse.

To correctly simulate the pulse evolution in the laser cavity and achieve the convergence, three key parameters must be decided with great care: the length of the temporal window, the sampling rate and the step size of the SSF method.

The temporal window and the sampling rate which are used to represent the pulse must be correctly set that both the temporal and the spectral window are wide enough to contain all the necessary information of the pulse. The length of the temporal window must be much longer than the pulse width. For example, a Gaussian pulse with FWHM = 500 fs, the time window must be at least as long as 5 ps so that all the important amplitude information of the pulse falls in the window.

The sampling rate decides the time interval of the two neighbor points in the

temporal window, which corresponds to the bandwidth of the spectral window. A shorter time interval corresponds to broader spectral window according to the Fourier transform. The bandwidth of the spectral window also must be much broader than the pulse bandwidth to guarantee correction of the calculation. Therefore, for a pulse with larger TB product, which extend the pulse duration for a fixed pulse bandwidth, more sampling points are always required.

For simulation on laser with uniform anomalous net dispersion, the pulse is nearly transform limited at all the positions in the laser cavity, so that 2^9 points should be enough. However, for a laser cavity with normal dispersion or has strong dispersion management, the pulse can be strongly chirped in the laser cavity, and much more points up to $2^{13} \sim 2^{15}$ can be required.

To achieve accurate simulation result, the spatial step length for the SSF method also must be carefully chosen. Normally, a smaller step size will increase the accuracy of the simulation but cost more computation time. It need to be noted that a step size smaller than the carrier wavelength is physically meaningless. On the contrary, a large step size reduces computation time but may lead to unacceptable calculation errors. The basic concept to chose the step size is that the step size must be much shorter than L_D and L_{NL} .

The simplest method is to use a constant step size, keep it short to guarantee the simulation accuracy and reliability. This method was used in most numerical research works on passively mode-locked fiber lasers[46, 92, 93]. It performs well for lasers with uniform anomalous net dispersion cavity and low cavity loss in which the pulses experience no much stretching and the peak power has nearly no variation. However, while there is a dispersion map in the cavity, pulses are strongly stretched and the

peak power can be scaled over tens of times along the cavity, and the nonlinear length also varies, as shown in equation (3.4). The reference L_{NL} must be the shortest one for choosing the constant step size, and the simulation becomes low efficient in saving computation time. In this case, employing step size varies with L_{NL} can increase the efficiency.

In this thesis, nonlinear phase-rotation method is used to decide the step size. Compared to other variable step size methods which are always used in optical fiber communication systems, this method is more accurate and efficient for systems with strong nonlinearity, such as passively mode-locked fiber laser. The step size is decide by equation (3.13)

$$h = \frac{\phi_{\text{NL}}^{\text{max}}}{\gamma P} \quad (3.13)$$

where h is the step size, $\phi_{\text{NL}}^{\text{max}}$ is the allowed maximum nonlinear phase shift and P is the peak power of the pulse. In this method, the maximum nonlinear phase shift per-step is limited. The step size will be adjusted according to pulse peak power. The average step size can be 1~10 times longer than the constant step size for different cavity design while the accuracy are kept the same. Therefore, the computation efficient is tremendously increased, especially for lasers with serious peak power variation in the laser cavity [94].

Figure 3.3 The simulation result on self-start mode-locking

Figure 3.3 shows an example of the simulation by correctly setting all the parameters. A stable mode-locking state can be built up and self-sustained from a noisy initial input after traveling many roundtrips in the laser cavity.

3.3. PULSE SHAPING MECHANISM IN PASSIVELY MODE-LOCKED FIBER LASERS

Soliton laser

Passively mode-locked optical pulse was firstly demonstrated in a laser cavity with net anomalous dispersion and small cavity loss. The fiber nonlinearity balanced the dispersion just like the soliton mechanism and generated optical pulse with hyperbolic-secant pulse profile. Therefore, such lasers are also named as “soliton laser” [62]. Soliton lasers were widely investigated at 1550 nm central wavelength, which is the C-band window for optical fiber communications. SMF can provide

anomalous dispersion at this wavelength, and EDF can provide high gain at the C-band of the communication window. Soliton lasers have the advantages nearly transform limited pulse profile and ultra-stable operation. The time jitter of a soliton laser can be as low as ~ 10 fs, which reaches the limitation of present commercial measurement techniques. Such pulses are desired for all-optical signal processing systems [95, 96].

Soliton lasers can be characterized from the optical spectrum. Figure 3.4 is the typical optical spectrum of a soliton laser. The laser is mode-locked by NPR mechanism and has a net dispersion of 0.34 ps/nm. The spectrum has a nearly hyperbolic profile and has sidebands on the spectrum wings which are the characteristic of the soliton lasers. For ideal soliton solution of the NLSE, there shall not be any sideband. In passively mode-locked fiber laser, the sideband is caused by the periodical modulation of the gain and loss in the laser cavity and accompanied by the dispersive wave at the trails of the pulse. Therefore, optical pulses generated by the soliton laser are actually quasi-solitons [97-99]. To increase the pulse quality, the loss of the laser cavity must be minimized. The location of the sideband is decided by the net dispersion of the laser cavity [97-99].

*Figure 3.4 Optical spectrum of a soliton laser***Dispersion managed soliton laser**

The nonlinear phase shift per-roundtrip can affect the stability of the laser. When the nonlinear phase shift of the pulse peak is larger than 2π , the soliton may break up. For a soliton laser constructed by SMF, the output pulse energy is always limited to a few pJ [35].

To achieve higher pulse energy, the stretched pulse laser has been proposed [30, 100-102]. In such laser, the anomalous dispersion of the SMF is compensated by inserting optical fiber with large normal dispersion into the laser cavity. The net dispersion of laser is small and can be either normal or anomalous. The laser cavity forms a periodical dispersion map and the period equals to one cavity roundtrip. Therefore, such laser is also known as dispersion managed soliton laser. Due to the large dispersion varying in one roundtrip, the pulse is temporally stretched and compressed in the laser cavity. The stretching will lead to lower average peak power of the pulse in the laser cavity compared to the transform limited pulse hence reduce the nonlinear phase shift. Furthermore, the stretched pulse is more robust to the nonlinear phase shift, and higher peak power can be supported [102]. The pulse energy can also be increased tens of times compared to conventional soliton laser. Generally, the output pulse of a stretched pulse laser is not transform limited, but nearly linearly chirped.

By proper designing the cavity dispersion map, bandwidth of a stretched pulse laser can be much larger than the soliton lasers [103]. Due to the soliton compression effect, the output pulse can be compressed to tens of fs by proper choosing the

location of the output coupler [72, 104, 105]. The pulse profile is nearly Gaussian rather than hyperbolic secant squared. The stretched pulse is a localized solution of the NLSE by considering the dispersion managed laser cavity. The pulse shaping mechanism is dominated by the balancing of the nonlinearity and the dispersion. Therefore, such laser is also referred to dispersion managed soliton laser. A typical spectrum of dispersion managed soliton laser is shown in Figure 3.5.

Figure 3.5 Optical spectrum of a dispersion managed soliton laser

Similariton laser

To achieve higher pulse energy, self-similarity of pulse propagation has been investigated [106]. It has been found that a parabolic pulse can keep its form with a scaling pulse width and pulse peak power while transmitting through a fiber amplifier with normal dispersion. This effect was soon adopted in chirped pulse optical amplification (CPA) system [107, 108]. In 2004, Ilday *et al* employed the self-similarity in passively mode-locked fiber laser for the first time [109]. The laser was operated at 1060nm central wavelength and the gain was provided by Ytterbium doped fiber (YDF). At this wavelength, conventional optical fiber has large normal

dispersion. They used grating pairs to compensate the normal dispersion and stable mode-locked optical pulse with high pulse energy (>1 nJ) was achieved. After that, numerous researches on similariton laser have been carried out. Recent works showed that similariton can also be achieved in a conventional dispersion managed laser cavity with normal net dispersion [110].

Figure 3.6 Optical spectrum of a similariton laser

The output pulse of a similariton laser always has large pulse width (several to tens of picoseconds) due to the strong pulse chirp. The chirp is nearly linear and can be compensated external the laser cavity, and then ultra-short pulse with sub-ps pulse width can be achieved.

The output spectrum of similariton laser shows identical property which has steep spectrum edges and relative flat spectrum top. Figure 3.6 shows the optical spectrum of a typical similariton laser with -0.6 ps/nm net dispersion.

The idea of constructing passively mode-locked fiber laser has been explored to hit the maximum pulse energy. Chong *et al* proposed an all-normal-dispersion laser (ANDi-laser) without any anomalous dispersion component in the laser cavity [44]. A

spectral filter was employed to stabilize the mode-locking instead of the grating pairs. In this scheme, over 10 nJ ultra-short optical pulse has been demonstrated in a YDF based laser. Pulse dynamics in erbium doped fiber laser with normal net dispersion has also been investigated. Due to the relative narrower gain bandwidth, the gain profile plays an important role in pulse shaping. Hence, the mode-locked pulse is also known as gain guided soliton [45].

3.4. CONCLUSIONS

The pulse shaping mechanism of each device in passively mode-locked fiber laser has been demonstrated. A numerical model was established based on the NLSE and the CGE. The nonlinear phase rotation method was used to increase the computation efficiency. By correctly setting the parameters, self-start mode-locking can be achieved by the simulation model.

The pulse shaping mechanism for different cavity design was also analyzed. According to different cavity dispersion, soliton, dispersion managed soliton and similariton could be achieved. Each pulse shaping mechanism could be identified from the optical spectrum of the mode-locked pulses.

4 NPR Mode-locked Laser with Dispersion Managed Cavity

4.1. INTRODUCTION

The pulse shaping mechanism in passively mode-locked fiber lasers decides the properties of the mode-locked pulse such as pulse energy, pulse temporal profile and pulse spectrum. Researches on the pulse shaping mechanism have been mainly focused on the function of the fiber nonlinearity, the cavity dispersion map or the intra-cavity spectral filter in the last decades [4, 38-40]. The saturable absorber was regarded as the key component for pulse self-starting, but its impact on pulse shaping didn't attract much attentions. As the importance of the dissipative process in the passively mode-locked fiber laser was realized recently [50, 111, 112], it's worthy to investigate the function of the saturable absorber in pulse shaping.

In this chapter, I investigate the effect of the saturable absorber in a dispersion managed soliton laser. The NPR technique is used to investigate the mode-locking under different saturable absorptions experimentally. It shows that the properties of

the saturable absorption can affect the pulse shaping in the laser cavity and lead to distinct mode-locking regimes.

In Section 4.2, a brief introduction to the mechanism of the NPR is given. Section 4.3 demonstrate that different mode-locking regimes can be achieved in a same dispersion managed laser cavity by rotating the wave plates. Section 4.4 shows that noise-like emission can also be observed in the same laser cavity. By correct setting the wave plates, high energy noise-like pulse can be achieved. In section 4.5, a dual-wavelength mode-locking is demonstrated using the spectra filtering effect of the NPR together with high birefringence fiber.

4.2. MECHANISM OF THE NONLINEAR POLARIZATION ROTATION MODE-LOCKING

The NPR mode locking technique exploits the nonlinear birefringence of the single mode optical fibers and uses it to realize an artificial saturable absorber effect with a polarization dependent element in the laser cavity for a self-started mode locking. The same effect of optical fibers was used previously for the polarization switching and optical pulse shaping. Hofer *et al.* were the first one who used the effect as a self-sustaining mechanism for passive mode-locking of fiber lasers [3]. The technique was then widely used for the self-started mode locking of ultra-short pulse fiber lasers.

In order to get insight into the NPR mode locking technique, it is worth briefly introducing the intensity dependent transmission effect of the NPR [113, 114]

Figure 4.1 Principle of NPR mode locking in fiber lasers

It is convenient to use a configuration as shown in Figure 4.1 to illustrate the mode locking principle of the NPR technique. A segment of linearly birefringent optical fiber is placed between two polarizers. Light of arbitrary polarization incident to the setup is transferred into linearly polarized light by the polarizer before the fiber. When the light further propagates in the fiber, it splits into two components along the two polarization axes of the fiber, respectively. After passing through the fiber, generally the polarization of the light becomes elliptically polarized. If the light intensity is weak, then the ellipticity of the light polarization will be fully determined by the linear fiber birefringence and the orientation of the polarizer. However, if the intensity of the light is strong, the nonlinear effects of the fiber must be considered. Then due to the nonlinear optical Kerr effect of the fiber, the polarization of the light after passing through the polarizer after the fiber (also called as analyzer) will as well become the light intensity dependent. Through appropriately selecting the orientation of the analyzer, a situation could be achieved that the stronger the light, the larger is the light intensity transmission through the analyzer. Physically, such a result is equivalent to that generated by a saturable absorber.

Therefore, if incorporating such a setup in a fiber laser, under the action of the artificial saturable absorber effect generated by the setup, mode locking of a laser

should be able to achieve. As the artificial saturable absorption is generated based on the optical Kerr effect, which has a recovery time in the order of several fs, from the laser mode-locking point of view, ultra-short mode-locked pulses could be generated by the technique.

To explain the mode locking mechanism mathematically, it is necessary to analyze the transmission of the laser cavity as shown in above Figure 4.1. The light transmission through the setup can be calculated by the Jones matrix method. Assuming that the two principal polarization axes of the birefringent fiber are the X (horizontal) and Y (vertical) axes; the polarizer and the analyzer are set in such positions that their polarization directions have an angle of θ and ϕ to the Y axis of the fiber polarization, respectively. Then the intensity transmission T of the light through the setup is,

$$T = \frac{I_{out}}{I_{in}} = \sin^2 \theta \sin^2 \phi + \cos^2 \theta \cos^2 \phi + \frac{1}{2} \sin(2\theta) \sin(2\phi) \cos(\Delta\Phi_F) \quad (4.1)$$

where $\Delta\Phi_F$ is the phase delay generated between the two light polarization components when they traverse the birefringent fiber. The phase delay actually consists of two parts: linear phase delay $\Delta\Phi_l$ caused by the linear birefringence of the fiber, this part always exists; and nonlinear part $\Delta\Phi_{nl}$ generated by the nonlinear effects of the fiber. If the light intensity is weak, the nonlinear part nearly becomes zero. Hence one can divide the light transmission into the linear transmission and the nonlinear transmission. The linear intensity transmission can be written as,

$$T_l = \sin^2 \theta \sin^2 \phi + \cos^2 \theta \cos^2 \phi + \frac{1}{2} \sin(2\theta) \sin(2\phi) \cos(\Delta\Phi_l) \quad (4.2)$$

Once the orientations of the polarizer and analyzer with respect to the fiber polarization principal axes are fixed, the linear transmission of the setup is a sinusoidal function of the linear phase delay between the two polarization components. Figure 4.2 below shows curves of the cavity linear transmission versus the total linear phase delay between the two polarization components, for the difference between the polarization directions of the polarizer and the analyzer varying from 0 to $\pi/2$, and when θ is equal to $\pi/4$.

Figure 4.2 The cavity transmission versus the phase delay

Figure 4.2 shows that linear system loss occurs at positions where the total linear phase delay between the two polarization components is an integer multiple of 2π when the difference between the polarization directions of the polarizer and the analyzer varying from $\pi/4$ to $\pi/2$. Therefore, if one sets the polarization controllers such that the light at particular wavelength λ is within the gain bandwidth of the EDF and satisfies this condition, mode locking can occur because the nonlinear refractive index changes the phase delay between the two polarization directions of the polarizer and the analyzer is offset from $\pi/2$, the difference between the maximum and minimum transmission of the system is decreased. This means that the mode-locked

pulse will be less stable because the CW light is not effectively rejected. Therefore, although the relative orientation between the polarizer and the analyzer could be arbitrarily selected, in order to possibly achieve a stable mode-locked operation, it is preferred to choose the relative orientation between the polarizer and the analyzer to be $\pi/2$. Under such selection the linear transmission is possible to be set to zero.

To illustrate the effect of the NPR on the intensity transmission, we assume that the nonlinear fiber birefringence only introduces small extra phase delay $\Delta\Phi_{nl}$. Then the intensity transmission can be written as,

$$\begin{aligned}
 T &= \sin^2 \theta \sin^2 \phi + \cos^2 \theta \cos^2 \phi + \frac{1}{2} \sin(2\theta) \sin(2\phi) \cos(\Delta\Phi_l + \Delta\Phi_{nl}) \\
 &\approx \sin^2 \theta \sin^2 \phi + \cos^2 \theta \cos^2 \phi + \frac{1}{2} \sin(2\theta) \sin(2\phi) \cos(\Delta\Phi_l) \\
 &\quad - \frac{1}{2} \sin(2\theta) \sin(2\phi) \sin(\Delta\Phi_l) \Delta\Phi_{nl} \\
 &= T_l - \frac{1}{2} \sin(2\theta) \sin(2\phi) \sin(\Delta\Phi_l) \Delta\Phi_{nl}
 \end{aligned} \tag{4.3}$$

The nonlinear phase delay introduces a transmission change relative to the value of the linear transmission T_l . The change is not only the nonlinear phase delay $\Delta\Phi_{nl}$, therefore, the light intensity dependent, but also the orientations of the polarizer and analyzer, as well as the linear phase delay dependent. As a result, in order to generate an artificial saturable absorber effect by the nonlinear fiber birefringent effect, it is necessary to appropriately select the combination of all these parameters.

It is instructive to consider a special case to illustrate it. Consider that the polarizer and the analyzer are set orthogonal. In this case the linear intensity transmission is

$$T_l = \sin^2 2\theta \frac{1 - \cos(\Delta\Phi_l)}{2} \quad (4.4)$$

Therefore, the maximum linear intensity transmission is limited by the factor of $\sin^2(2\theta)$. The intensity transmission under the existence of nonlinear phase delay $\Delta\Phi_{nl}$ is

$$T = T_l + \frac{1}{2} \sin^2 2\theta \sin(\Delta\Phi_l) \Delta\Phi_{nl} \quad (4.5)$$

The orientation of the polarizer determines the projection of the light on the two polarization axes of the fiber, therefore, determines whether positive $\Delta\Phi_{nl}$ or negative $\Delta\Phi_{nl}$ would be generated. Assuming that negative $\Delta\Phi_{nl}$ is generated, then further depending on the linear phase delay, the NPR could cause either an increase or decrease in the intensity transmission. The magnitude of $\Delta\Phi_{nl}$ is always proportional to the intensity of light. This means that with the increase of the light intensity, either an increase or a decrease in the transmission could be generated, which is purely determined by the linear phase delay selection. It shows that the by changing the phase delay, the saturable absorption of the NPR can be modified.

4.3. MULTIPLE STABLE MODE-LOCKING STATES IN A DISPERSION MANAGED LASER CAVITY

As introduced in Chapter 3, there are three operation regimes for passively mode-locked fiber lasers. Each operation state corresponds to distinct pulse properties such as pulse spectrum, pulse energy and pulse chirp. The operation regimes are important for fiber laser design. To achieve stable pulse train with low noise, the

soliton laser shall be applied; to achieve high pulse quality, dispersion managed soliton laser is always used to suppress the dispersive wave; to achieve high pulse energy, similariton laser shall be the best choice [32, 95, 115, 116].

Conventionally, the changing of operation regimes is always accomplished by modifying the dispersion map of the laser cavity [3]. The question is: whether the dispersion map is the only parameter which decides the operation regimes of the passively mode-locked fiber lasers?

In this section, the effect of the saturable absorber on the pulse shaping mechanism is investigated. Theoretical analysis shows that the by increasing the modulation depth of the saturable absorber, the self-start mode-locking evolves from similariton, dispersion managed soliton to soliton-like pulses in a dispersion managed laser cavity with small normal net dispersion. An experimental setup based on NPR is also demonstrated. Without changing the dispersion map, self-start mode-locking with distinct optical spectrum are achieved by adjusting the orientation of the wave plates. The mode-locking states can be identified to different pulse shaping mechanism. The result confirms that other than dispersion map design, the properties of the saturable absorption can also be a factor to decide the pulse shaping mechanism.

Simulation & Experiment

The numerical model introduced in Chapter 3 is used to investigate a passively mode-locked fiber laser with dispersion managed laser cavity. The laser is consists of 8 m EDF with normal dispersion of -63 ps/nm/km and 17 m SMF with anomalous dispersion of 18 ps/nm/km. The net dispersion is then around -0.22 ps/nm. The nonlinear coefficient of the fibers is 3 W/km. The saturation power of the saturable absorber is 10 W. The linear cavity loss is 3 dB, includes the output coupling and

cavity splicing loss. The saturation energy of the EDF is 1 nJ, and the gain bandwidth is 20 nm.

In the simulation, the gain and the modulation depth of the saturable absorber are used as variables. The initial pulse is white noise with randomly varying amplitude.

When the modulation depth is smaller than 0.05, mode-locking can not be self-started. While $I_0 > 0.05$, mode-locking can be self-started. The spectrum has steep edges with a relatively flat top which are the typical characteristics of similariton mode-locking with normal net dispersion.

By increasing the modulation depth to 0.4, the steep edges of the spectrum disappear. The pulse spectrum has smooth profile with minimized sideband. In previous report, such spectrum could be achieved in a passively mode-locked fiber laser by carefully control the net dispersion [103].

Further increase the modulation depth to 0.5, and the spectrum shows typical properties of dispersion managed soliton with complex spectral profile and strong sidebands..

When the modulation depth is increased to above 0.6, spectrum is similar to the soliton mode-locking with strong sidebands, which is always observed in an anomalous net dispersion laser cavity [117].

The simulated spectrums of the mode-locked pulses are shown in Figure 4.4 to Figure 4.7 when the modulation depth is 0.2, 0.4, 0.5 and 0.6, respectively. For each result, the gain is 0.07, 0.083, 0.088 and 0.1 respectively.

To confirm the theoretical result, a passively mode-locked fiber laser with dispersion managed laser cavity is experimentally established to investigate the multiple stable regimes. NPR mechanism is employed to provide variable saturable absorption.

Figure 4.3 Experiment setup of the dispersion managed soliton laser

The laser setup is shown in Figure 4.3 [118]. All components in the laser cavity are fiber-based or with fiber pigtails. A polarizer is mounted on a fiber bench to provide polarization dependent loss, 2 PCs are mounted beside it. The PCs are composed of 2 quarter wave plates or 2 quarter wave plates and a half wave plates respectively. The laser gain is provided by 8 m high-doped EDF with -63 ps/nm/km dispersion, a 17 m length of standard single mode fiber with 17 ps/nm/km dispersion is applied in the cavity to provide dispersion stretching. The fundamental repetition rate is 8 MHz. The net dispersion of the cavity is around -0.22 ps/nm. An isolator is used to guarantee the laser operate in unidirectionally. Laser output is provided by a 10/90 fiber coupler.

By carefully adjusting the pump power and the wave plates on the fiber bench, self-start mode-locking can be observed. conventionally, a passively mode-locked fiber laser with fixed dispersion map generates optical pulse with identical spectral profile [3]. The bandwidth of the spectrum may vary according to the pump power and the orientation of the wave plates, but the spectral profile always keeps its shape. However, in this experiment, it is notice that by rotating the wave plates on the fiber bench, self-start mode-locking can be achieved with distinct pulse spectrum corresponding to different pulse shaping mechanism. Just as the simulation results reveal, by modifying the parameters of the storable absorber, the laser can be mode-locked according to different pulse shaping mechanism. Figure 4.4 to Figure 4.7 show the spectrums of different mode-locking states achieved by changing the orientation of the wave plates.

Figure 4.4 Optical spectrum of the self-similar mode-locking

Figure 4.4 demonstrate both the simulation result and the experimental result of the optical spectrum which have the typical characteristic of the similariton. The pulse can be characterized by the steep edges of the pulse spectrum. The pump power in the experiment is 112 mW, while the threshold for mode-locking is 108 mW.

Figure 4.5 shows the experimental spectrum and the simulation spectrum of the mode-locking regime without either sideband or steep spectrum edge. In this case a stronger modulation depth is needed and a higher gain is required. The pump power used in the experiment is 134 mW while the threshold is 127 mW. The losing of steep edges of the spectrum indicates that the pulse is no longer parabolic and the evolution of the pulse doesn't follow the self-similar process. The laser is working under dispersion managed soliton regime.

Figure 4.5 Optical spectrum of the dispersion managed soliton with minimized sidebands

The minimized sideband in Figure 4.5 reveals that the dispersive wave of the pulse is effectively suppressed. It has been reported that to eliminate the sidebands in the dispersion managed soliton laser, the dispersion map of the laser cavity must be carefully designed and the net dispersion shall be near to zero [103]. However, by examining Figure 4.5 and Figure 4.6, both the simulation and the experimental results here show that other than the cavity dispersion, the characteristics of the saturable absorber also is an important factor to control the dispersive wave.

Figure 4.6 is the optical spectrum of the stable mode-locking with typical spectrum of dispersion managed soliton. In the experiment, the pump power is 148 mW while the mode-locking threshold is 144 mW. Without modifying the laser cavity, strong spectrum sidebands emerge by modifying the saturable absorber.

Figure 4.6 Optical spectrum of the dispersion managed soliton with strong sidebands

Figure 4.7 (a)Simulation result and (b)Experimental result of the optical spectrum of the mode-locking state with a soliton-like optical spectrum

It can be seen from the simulation result that an increasing of modulation depth induces the laser mode-locking shifts from self-similar pulse to dispersion managed

soliton. If further increase the modulation depth to 0.6, and the gain to 0.1, the pulse spectrum will show some characteristics of soliton laser with strong sidebands, as Figure 4.7(a) shows. Such spectrum is also observed in the experiment by rotating the wave plates, as shown in Figure. The pump power is 168 mW while threshold is 164 mW pump power. The spectrum shows strong asymmetric which can be caused by the third-order dispersion [119].

Figure 4.8 Oscilloscope trace of the harmonically mode-locked pulse with 1.02 GHz repetition rate

The experimental results fit well with the simulation result. Multiple stable mode-locking states are observed according to different pulse shaping mechanism. Each mode-locking state can be self-started, and the state is only decided by the orientation of the wave plates. Increasing or decreasing of the pump power will not change the typical characteristic of the pulse spectrum. By increasing the pump power, multiple pulses can be generated and harmonic mode-locking of each mode-locking

state can be observed. Figure 4.8 shows the oscilloscope trace when the laser is harmonically mode-locked with 1.02 GHz repetition rate.

Discussions

In 1998, Nijhof *et al* demonstrated that the effective dispersion could be shifted to the anomalous region in a dispersion managed fiber system due to the fiber nonlinearity [43]. Due to the fiber nonlinearity, in anomalous dispersion fiber, the pulse always has broader bandwidth than in normal dispersion fiber. It is well known that the dispersion induced pulse chirp is proportional to the square of the pulse bandwidth. Therefore, the pulse chirping in anomalous fiber part is increased due to its broader bandwidth, and makes the effective dispersion shift to anomalous. Stronger nonlinearity can induce stronger pulse breathing thus inducing stronger dispersion shift. It indicated that a dispersion managed soliton can be achieved in a dispersion map with normal net dispersion.

Recently, the condition for self-similar pulse evolution in a dispersion managed fiber system with normal net dispersion has been investigated [110]. It has been revealed that while the nonlinear effect is weak, the system can support self-similar propagation. However, while the nonlinearity is strong, the self-similar propagation will break due to the stimulated modulation instability caused by the anomalous dispersion fiber, and the dispersion managed soliton mechanism dominate the pulse propagation.

To investigate the physical significance of the multiple stable mode-locking regimes, the nonlinear phase shift of the mode-locked pulse within one round trip of the laser cavity is calculated according to the equation (4.6).

$$\phi_{NL} = \int_0^L P_{\max} \gamma dl \quad (4.6)$$

where $P_{\max}$ is the peak power of the pulse. The calculation parameters are the same to that have been used in the Figure 4.4 to the Figure 4.7. The results are listed below:

- Similariton: 0.72
- Dispersion managed soliton with minimized sideband: 0.89
- Dispersion managed soliton with sideband: 1.15
- Soliton-like pulse: 1.93

It can be seen that while the nonlinear phase shift is small, which correspond to a weak nonlinear effect, similariton is achieved. Increasing of the nonlinear phase shift leads to dispersion managed soliton operation of the laser. Further increasing the nonlinear phase shift drives the effective net dispersion to anomalous and finally leads to a soliton-like pulse spectrum. The simulation results are in good accordance to the analysis of reference [43, 110].

As the nonlinear phase shift is in proportion to the pulse peak power, it is to say, the higher modulation depth enables higher pulse peak power due to the stronger pulse shortening effect as well as stronger nonlinear effect and drives the dispersion managed laser working under different regimes.

In summary, the saturable absorber can be an important factor in pulse shaping process in a dispersion managed laser. Other than the cavity dispersion map, the properties of the intensity modulation shall also be carefully set to achieve the desired mode-locked pulse.

4.4. HIGH ENERGY NOISE-LIKE PULSES

The characteristics of the saturable absorber not only can drive the laser working under different stable mode-locking regimes, but also can drive the laser generating noise-like pulses. With the same experiment setup shown in Figure 4.3, noise-like emission can be observed by changing the orientation of the wave plates.

Noise-like operation of fiber laser was firstly reported by Horowitz *et al* in 1997 [120]. Formation of the noise-like pulse was attributed to the internal birefringence of the laser cavity combined with the nonlinear transmission and the laser gain. Normally, noise-like emission is regarded as a detrimental effect in the passively mode-locked fiber laser which is aiming for generating ultra-short optical pulses. However, it has been shown recently that in some applications such as metrology illumination system, noise-like operation of the passively mode-locked fiber laser can be an attractive light source due to its broad spectrum, high pulse energy and low coherence length [121, 122]. Therefore, intensive investigations on noise-like emission have been done in recent years [11, 123-125].

The noise-like pulse actually is a bunch which includes many small pulses with randomly varying peak power, pulse width and pulse location. Recent researches on noise-like pulses have been focused on achieving maximum bandwidth, or extra large pulse energy. According to the previous reports, the noise-like pulse generally circulated in the laser cavity with the fundamental repetition rate of the laser, therefore, the pulse energy was thought to be only related to the pump power and the cavity design [123].

In this section, the dynamics of noise-like pulses is investigated experimentally. It shows that the noise-like pulses can split into multiple pulses by changing the laser pump or adjusting the wave plates. The repetition rate of the noise-like pulse is not necessarily equal to the laser fundamental repetition rate, but can be switched to different harmonic orders by changing the cavity properties [126]. By proper setting the wave plates, noise-like pulse with high pulse energy (28 nJ) can be achieved.

Figure 4.9 Optical spectrum of the noise-like pulse

The noise-like emission has a high threshold of 800 mW. The spectrum of the noise-like pulse is shown in Figure 4.9. The bandwidth of the spectrum is 22 nm. The repetition rate of the pulse is equal to the fundamental frequency of the laser cavity which is around 8 MHz. The average output power is 43 mW, which corresponds to 5.4 nJ pulse energy. The pulse spectrum has a peak at 1700 nm, which is far from the gain spectrum of the EDF. Since the central emitting wavelength of the laser is around 1580 nm, this peak just falls in the Raman scattering range of the laser emission. Furthermore, this peak can be eliminated by decreasing the pump power. As there are no other mechanism to generate emission at 1700 nm, it can be confirmed that this

peak is caused by the intra-cavity Raman scattering. The strong Raman peak indicates that the peak power of the noise-like pulse is very high.

Figure 4.10 Oscilloscope trace of the (a) fundamental mode-locking (b) 4th harmonic mode-locking (c) fundamental mode-locking of the giant pulse

By increasing the pump power, the noise-like pulse can split into multiple pulses. Monitoring by a 350 MHz oscilloscope, It is notice that the process of multiple noise-like pulse formation follows a manner of pulse radiation. When the pump power is increased to 1.1 W, the fundamentally mode-locked noise-like pulse emits a pulse and move away from the original pulse. After around 1 sec, the emitted pulse reaches the center of the two original pulses and forms the 2nd order harmonic mode-locking. By

further increasing the gain, more pulses will be generated and maximum 4th order harmonic mode-locking can be obtained when the pump power is 1.7 W.

If further increase the pump power when the laser is 4th order harmonic mode-locked, the pulses will not split into higher order harmonic mode-locking, but combine together and form a giant pulse at the fundamental repetition rate. The giant pulse doesn't split even when the pump power is increased to 2.5 W. To avoid the damaging of the devices, the pump power is kept below 2.5 W in the experiment. The maximum output power achieved is 230 mW, corresponding to over 28 nJ pulse energy. If then decrease the pump power, the giant first split into 4th order harmonic mode-locking, then reduce to 3rd, 2nd, and fundamental mode-locking.

To investigate the mechanism of pulse splitting, a 45 GHz photodetector and a 50 GHz high speed oscilloscope are used to monitor the evolution of the noise-like pulse. Figure 4.11 shows the pulse profile of the noise-like pulse at different pump powers.

When pump power is 800 mW, the noise-like pulse has 40 ps pulse width and 180 mV peak voltage on the oscilloscope, as shown in Figure 4.11(a). By increasing the pump power to 1 W, both the pulse width and the peak voltage increase. The pulse width is 54 ps and the peak voltage is 250 mV, as shown in Figure 4.11(b). When the pump power is further increased to 1.05 W, the pulse emits energy and shows a long trail on the oscilloscope, as in Figure 4.11(c). Further increasing the pump power will lead to new pulse formation from the trail and harmonic mode-locking of the laser. The process repeats and maximum 4th order harmonic mode-locking can be achieved by increasing the pump power. However, when the pump power is above 1.7 W, the harmonic mode-locking recovers to fundamental mode-locking and forms a giant

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pulse. When the pump power is 2.5 W, the giant pulse has 250 mV peak voltage and over 280 ps pulse width, as shown in Figure 4.11(d).

Figure 4.11 Oscilloscope trace of the noise-like pulses when the pump power is (a) 800 mW (b) 1 W (c) 1.05 W (d) 1.7 W

Such pulse splitting and recombination can also be observed by tuning the position of the wave plates. The only difference is that, maximum 7th order harmonic mode-locking can be achieved by rotating the wave plates. It reveals that the noise-like pulse splitting is strongly related to the properties of the saturable absorption in the laser cavity.

Figure 4.11 shows that the peak voltage of the detected noise-like pulses is

limited to below 250 mV, which reveals that the peak power of the noise-like pulses is clamped. This mechanism is much similar to the mechanism of multiple soliton formation, which is attributed to the peak power clamping effect of the saturable absorber [92]. Normally, the saturable absorber provides positive feedback to the laser cavity. With the increasing pump power, the peak power of the pulses increases. When the peak power of the pulse is higher than a threshold, the saturable absorber can be overdriven and induces negative feedback to the laser cavity, and light has lower power is primarily amplified by the laser gain, and forms the pulse trail. Further increasing of the gain will build up new noise-like pulse from the trail and lead to harmonic mode-locking [92]. Therefore, multiple noise-like pulses can be formed by either increasing the laser gain which increases the pulse peak power or rotating the wave plates which change the overdriven threshold.

It is interesting that the multiple pulses can combine into a giant pulse by increasing the pump power. This behavior allows to achieving noise-like pulses with very high pulse energy as 28 nJ. Such combination phenomenon can be caused by the pulses interaction though the pulse trails [127-129].

Due to the Kerr nonlinearity, an optical pulse can modulate the local effective refractive index of the fiber, and the modulation amplitude is in proportional to the pulse intensity. While two pulses in an optical fiber are near in the temporal domain, and the pulse trail overlap, the modulation on refractive index induces interaction between the pulses by affecting the propagation velocities. The interaction can be either attraction or repulsion. When the interaction is attraction, the pulse can be bound together [103]. To analytically investigate the interaction requires full information about the pulse amplitude and the phase. As the noise-like pulse is with random phase, the interaction

can be extremely complicated.

In this experiment, the pulse energy of the recombined pulse is only limited by the laser gain. Higher pulse energy can be expected by comprising the laser cavity with devices which support high optical power.

In summary, noise-like emission in the passively mode-locked fiber laser is achieved by adjusting the NPR. It shows that the properties of the saturable absorption can affect the dynamics of the noise-like pulses. By correctly setting the NPR, noise-like pulses with high peak power and high pulse energy is achieved.

4.5. DUAL-WAVELENGTH MODE-LOCKING

Current optical fiber communication networks increasingly rely on WDM technology in conjunction with optical time-division multiplexing (OTDM) of individual WDM channels. The combination of high-repetition-rate data streams with a large number of WDM channels has pushed transmission performance in terrestrial and transoceanic links to nearly 1 Tb/s. This has created a demand for all-optical transmission sources that can generate ps mode-locked pulses at various wavelengths, i.e., WDM-OTDM sources. Recently, there have been a number of experiments that have demonstrated the feasibility of mode-locking at different wavelengths [98, 130, 131].

Multi-wavelength outputs in CW type and actively mode-locking type of EDF and SOA laser have been thoroughly investigated. In the latter case, the necessary framework for the theoretical analysis of the relevant deployed technique has been also recently established. But multi-wavelength ultra-short pulse output in passive mode locked fiber ring laser has not yet been addressed so far.

In this section, a passively mode-locked fiber laser for this multiple-wavelength mode-locking is demonstrated, and dual-wavelength mode-locking can be achieved.

The laser is mode-locked by the NPR mechanism. In NPR mode-locked fiber laser, the polarizer in the laser cavity can not only provide saturable absorption, but also spectral filtering effect in a fiber cavity with strong birefringence. By incorporating two sections of polarization maintaining fibers, dual-wavelength ultra-short pulses output simultaneously around 1558nm and 1570nm are observed. They have a pulse width of 2.4 ps and 2.1 ps respectively and they have the same direction of polarization [26].

Lyot filter

As described in (4.2), the linear transmission of the polarizer depends on the linear phase shift. By assuming the refractive index difference between the two principle axes keeps invariant for all the wavelength, the linear phase delay of the high birefringence fiber is:

$$\Delta\Phi_L = \frac{2\pi\Delta nL}{\lambda} \quad (4.7)$$

If the optical fiber between the two polarizers has strong birefringence, the linear delay would be wavelength dependent and forms filtering effect. When θ and ϕ in the equation are fixed at $\pi/4$ to the principle axis of the fiber, the transmission of the NPR is:

$$\begin{aligned} T &= \frac{I_{out}}{I_{in}} = \frac{1}{2} [1 + \cos(\Delta\Phi_L)] \\ &= \cos^2\left(\frac{\Delta\Phi_L}{2}\right) = \cos^2\left(\frac{\pi\Delta nL}{\lambda}\right) \end{aligned} \quad (4.8)$$

By assuming $\Delta\lambda \ll \lambda_0$, the transmission at the wavelength $\lambda = \lambda_0 + \Delta\lambda$ is:

$$T = \cos^2\left(\frac{\pi\Delta n L}{\lambda}\right) = \cos^2\left[\frac{\pi\Delta n L(\lambda_0 - \Delta\lambda)}{\lambda_0^2}\right] \quad (4.9)$$

The beat length of the birefringent fiber is defined as

$$\frac{\Delta n \cdot L_B}{\lambda_0} = 1 \quad (4.10)$$

the wavelength dependent transmission is:

$$T = \cos^2\left[\frac{\pi L(\lambda_0 - \Delta\lambda)}{L_B \lambda_0}\right] \quad (4.11)$$

The transmission of the NPR varies periodically according to the wavelength, and forms the so called Lyot filter [132]. The free spectral range (FSR) of the Lyot filter is:

$$F = \frac{\lambda_0 L_B}{L} \quad (4.12)$$

Figure 4.12 shows the transmission of a Lyot filter with $L_B / L = 100$ and $\lambda_0 = 1550$ nm.

Figure 4.12 Wavelength dependent transmission of a Lyot-filter

Therefore, by inserting optical fiber with high birefringence into the NPR mode-locked fiber laser, a comb filter can be formed and it is possible to achieve laser emission with multi-wavelength simultaneously.

Dual wavelength mode-locked fiber laser

Figure 4.13 Schematic of the dual wavelength passive mode-locked fiber ring laser; PI: polarization dependent isolator

Figure 4.13 shows the configuration of the dual wavelength passive mode locked fiber ultras-short pulse ring laser. The loop length of the laser cavity is about 22 m, which comprises of about 8 m long EDF. Total cavity loss is around 2.0 dB except the EDF. A Keopsys Raman Fiber Laser at 1480 nm is used to pump the laser. Unidirectional operation of the laser is enforced by the inclusion of a polarization-independent isolator in the cavity. There are two PCs consists of the wave plates as shown in Figure 4.13. The combination of the normal dispersion value of the EDF and the anomalous dispersion of the single mode fiber leads to a total cavity dispersion of around 20 fs/nm at 1550nm wavelength. Two pieces of polarization maintaining fibers (PMF) with length of 113 cm and 67 cm respectively are inserted into the

cavity. The tested beat length of the PMF is around 1.2 cm. Different phase shifts work together with the polarizer in the cavity leading to a filter effect. The separation $\Delta\lambda$ between two passband peaks can be estimated by:

$$\Delta\lambda \propto \frac{L_B}{L_1 \pm L_2} \quad (4.13)$$

where L_B is the beat length of the PMF, L_1 , L_2 are the lengths of the PMFs in the cavity. Then here the estimated corresponding $\Delta\lambda$ are about 12 nm and 45 nm respectively.

By careful adjustment of the wave plates, self-started dual-wavelength mode locking is observed. Sometimes, only one of the wavelengths achieves mode locking while the other mode may still be lasing CW if the PCs are not in the perfect positions. Figure 4.14(a) shows the dual wavelength ultra-short pulse laser spectrum from the laser's direct output with a pump power of 200 mW. There are two simultaneous mode-locking wavelengths that have peak wavelengths around 1558 nm and 1570 nm respectively. The approximate spectral bandwidths for each wavelength ultra-short pulse are 2 nm and 3 nm respectively. Both these peak wavelengths can be shifted up to a maximum of 4 nm and the spectral widths can be varied a little by tuning the wave plates. Both these wavelength ultra-short pulses are accompanied by one or two CW components because of the high Raman pump power (minimal pump output power is 60 mW at start-up). If the pump power is lower than 180 mW, mode-locking of the dual-wavelengths would be unstable.

Note that in Horowitz's report, he indicated that the walk off of the pulse in high-birefringence fiber would lead to noise-like emission [120]. In the experiment,

the birefringence is even higher than that in [120]. However, instead of noise-like emission, stable mode-locking with dual-wavelength emission is achieved. As high energy noise-like pulse has been achieved in a laser cavity with low birefringence in the previous section, the experimental results reveals that the noise-like emission shall be mainly attributed to the soliton collapse mechanism which is mainly decided by the properties of the saturable absorption [127].

Figure 4.14 Optical spectrum of (a) the dual-wavelength ultra-short pulse (b) Single wavelength ultra-short pulse spectrum after filter

A tunable filter with a 3 dB bandwidth of 5.8 nm is used to filter out shorter wavelength, as shown in Figure 4.14 (b). The output powers, after the filter, are 2.0 mW and 4.4 mW respectively for each wavelength. Later a 45 GHz Newfocus photo detector is used to detect the signal. A clear frequency component of 9.24 MHz with 50 dB SNR is seen on the spectral analyzer. It is the fundamental round trip frequency of the cavity. Figure 4.15(a) shows the temporal domain profile from the wide band oscilloscope. It shows that the laser has a period of 108 ns, which is same to the fundamental cavity frequency. The autocorrelator shows that it has an autocorrelation trace width of 3.6 ps. Therefore, as shown in Figure 4.15(b), the true pulse width is 2.4 ps if hyperbolic profile were assumed. Similarly, when only the

longer wavelength spectrum is filtered out, the same repetition rate of 9.24 MHz is obtained. The autocorrelation trace width is 3.2 ps and true pulse width is 2.1 ps if hyperbolic profile were assumed. The two wavelength ultra-short pulse outputs have the same phase on the oscilloscope. The time bandwidth product are 0.5 and 0.7 respectively, which implying that the outputs have small chirp values and is not transform-limited.

According to the Von der Linde method, the amplitude fluctuations are calculated as 2.68% and 1.55% respectively [85]. The timing jitters are about 2.34×10^{-6} and 3.44×10^{-6} . Since the pulse interval is 108 ns, the timing jitters of the pulse trains are approximately 252 fs and 371 fs, respectively.

Figure 4.15 (a) Time domain ultra-short pulse profile from oscilloscope (b) autocorrelation trace for 1558nm ultra-short pulse

Another fiber bench, with an additional rotatable polarizer, is used. It is observed that, the two wavelength ultra-short pulses show the same trend of rise/fall in power when the additional rotatable polarizer is tuned. The output state of polarization is also tested by using a polarization analyzer. It is found to be highly elliptical with both the wavelengths have almost the same polarization state. Both of

them are very stable during a period of one hour in the lab. Furthermore, no pulse width changes are observed. It is inferred that the existence of the multi-wave-mixing effect in the cavity enhances the stability of the dual wavelength outputs and binds them in the same polarization state.

It is well known the homogeneous broadening gain of EDF will induce strong gain competition and impact the stability of multi-wavelength of the fiber laser. It's a routine method to use the nonlinearity to compensate the gain competition in mode-locked fiber lasers while the four wave mixing (FWM) gain helps to flatten the net gain of the cavity [133]. Therefore, the pulse power shall be high enough to achieve multi-wavelength mode-locking.

The gain bandwidth of the Erbium fiber has a limitation of about 30 nm. According to (4.12), increasing the PMF length or using a PMF with shorter beat length can lead to smaller wavelength spacing $\Delta\lambda$. If the $\Delta\lambda$ is smaller, then there would have more mode locking wavelengths in the EDF bandwidth. For example, theoretically, a $\Delta\lambda$ of 8 nm will approximately lead to 3 mode-locking wavelengths. However, the output pulse-width of each wavelength will be broader and the peak power of each wavelength will also be much weaker. As a result, it reduces the nonlinear effect and impacts the achievement of stable multi-wavelength mode-locking. Therefore, to increase the wavelength number shall be challenging and difficult.

There are some reports about multiple wavelength oscillation with spacing near to ITU grid in a passively mode-locked fiber laser [134, 135]. In this case, each wavelength joined mode-locking process as CW light and should not be considered as multi-wavelength mode-locking.

In summary, by incorporating two pieces of PMF in the laser cavity, a filter is formed. Dual wavelength ultra-short pulse outputs around 1558 nm and 1570 nm are observed simultaneously, having a pulse width of 2.4 ps and 2.1 ps respectively and having the same polarization direction.

4.6. CONCLUSIONS

In this chapter, the effect of the saturable absorption to a passively mode-locked fiber laser with dispersion managed cavity is investigated. Mode-locking with different pulse shaping mechanism could be achieved in the same laser cavity by changing the modulation depth of the saturable absorber. The increasing of modulation depth increased the peak power of the self-started mode-locked pulses and drove the net dispersion of the laser cavity shift to anomalous range, and multiple mode-locking states could be observed in the laser cavity without changing the net dispersion. Therefore, the modulation depth should be considered as a freedom to design the dispersion managed soliton laser besides the dispersion map of the laser cavity.

Furthermore, by changing the orientation of the wave plates in the NPR module, noise-like emission was also observed in the experiment. It is confirmed that the properties of the saturable absorption could affect the dynamics of the noise-like pulses. By correct setting the NPR module, a giant pulse with high pulse energy has been observed. The pulse energy was only limited by the net gain of the laser cavity and maximum 28 nJ noise-like pulse was achieved experimentally.

By inserting 1.8 m length of PMF into the laser cavity, the NPR could also act as a comb-like spectral filter with 12 nm wavelength spacing. Unlike the result of ref

[120], the high birefringence laser cavity doesn't induce noise-like emission. Dual-wavelength ultra-short optical pulses are achieved at 1558 nm and 1570 nm simultaneously. The pulse widths are 2.4 ps and 2.1 ps respectively while the pulse bandwidths are 2 nm and 3 nm respectively.

5 All-Normal-Dispersion Passively Mode-locked Fiber Lasers

5.1. INTRODUCTION

With the development of modern technology, ultra-short optical pulses with high pulse energy are widely required for various applications. For example, such optical pulse can be used to generate exceptionally wideband, or supercontinuum, light sources that find numerous applications in biomedical imaging and coherence tomography [136, 137]. Therefore, generating higher energy ultra-short pulses is attractive for further progress in science.

Passive mode-locking of fiber lasers is a competitive technique to generate ultra-short optical pulses. In soliton laser or dispersion managed soliton, ultra-short pulses are shaped by the balancing of the nonlinearity and the dispersion. Under such mechanism, the peak power of the pulse increases tremendously with increasing pulse

energy. However, the high nonlinear phase shift per-roundtrip of the pulse will lead to unstable operation such as multiple-pulsing or noise-like emission which is harmful for generating high energy ultra-short optical pulses, as shown in chapter 4. For soliton laser, typical pulse energy is tens of pJ [42]. For dispersion managed soliton laser, typical pulse energy is hundreds of pJ [100].

The conventional method to generate high energy ultra-short pulses is incorporating a cascade of delicate CPA amplifiers at the output of such mode-locked laser oscillators [9, 27, 107]. Since the amplifiers greatly increase the complexity of the system, intensive research work has been done on achieving high energy ultra-short pulse directly from the mode-locked oscillator to reduce the cascade number of the amplifiers or even remove the amplifiers. Recently, it was shown that high energy pulses could be produced by a single solid-state laser, reducing the need for amplifiers [138]. Fiber lasers are also studied in that respect.

It has been found that constructing passively mode-locked fiber lasers with normal dispersion fiber can significantly increase the pulse energy. The pulses are shaped by the dissipative process of the nonlinear gain and the loss in such lasers. In optical fiber with normal dispersion, both the nonlinearity and the dispersion will provide positive chirp to the pulse, so that the pulses in the laser cavity are usually strongly chirped along the cavity, making them always as wide as tens of ps in the temporal domain. Such pulses can tolerate high nonlinear phase shift due to the self-similar evolution of the pulse, thus increasing the achievable pulse energy [109]. The ps pulses can be compressed to fs range by compensating the normal dispersion external the laser cavity [31, 139].

In a passively mode-locked fiber laser with a normal dispersion laser cavity, the pulse shortening effect is necessary to compress the pulse, thus balancing the pulse broadening effect. Otherwise the pulse will keep broadening and evolve to CW laser. Ilday *et al* proposed the similariton laser in which a grating pairs is employed in the laser cavity to compensate the aggregate positive chirp per-roundtrip and compress the pulse [140]. However, bulky grating pairs break the all fiber structure and reduce the robustness of the laser.

Soon after Ilday's demonstration, it has been found that the gain filtering effect of EDF can stabilize passive mode-locking in a NPR mode-locked EDF laser, and the mode-locked pulse was named as "gain guided soliton" [45]. In 2006, Chong *et al* demonstrated an all-normal-dispersion passively mode-locked fiber laser (ANDi-laser) in which an intra-cavity spectral filter is used to shape the pulse [44]. Since the pulse is strongly chirped, the red-shift light and the blue-shift light are located at the pulse wings. A spectral filter can block the light at the pulse wings and strongly shorts the pulse. With the pulse shaping of the spectral filter, which was thought to be the main mechanism of the pulse shaping, ultra-short optical pulse with over 10 nJ pulse energy has been achieved in Yb-doped fiber laser [64].

Theoretical works on passively mode-locked fiber laser with large normal net dispersion have also been developed [33, 46, 65, 141, 142]. Recent works showed that although spectral filter can help pulse shaping in the ANDi-laser, it also induces multiple pulsing operation of the laser [141, 143]. Narrower bandwidth of the spectral filter benefits more pulses. The multiple-pulsing phenomenon limits the pulse energy and should be avoided in laser design.

Another interesting discover is that the increasing of net normal dispersion can significantly increase the pulse energy [93]. However, the large normal dispersion also reduces pulse bandwidth. In passively mode-locked fiber lasers, high pulse energy and broad bandwidth are always required simultaneously to achieve ultra-short pulse with high peak power. At present, there is no ultimate guideline for the designing of laser cavity with large normal net dispersion.

In this chapter, I investigate the pulse dynamics in ANDi-lasers.

Section 5.2 investigates the mechanism of multiple pulsing. It shows that the properties of saturable absorber can be a freedom to optimize the laser design. By increasing the modulation depth, the maximum bandwidth and the maximum energy of the pulse can be significantly increased. .

Section 5.3 discusses the optimizing on the net dispersion to achieve maximum pulse energy without reducing the bandwidth.

In section 5.4, an NPR mode-locked fiber laser with normal net dispersion is demonstrated experimentally. By optimizing the net dispersion and the orientation of the wave plates, high energy ultra-short optical pulse can be achieved.

Section 5.5 investigates the complex gain profile of the EDF in the passively mode-locked fiber laser with normal net dispersion and demonstrates a wavelength switching phenomenon.

5.2. MULTIPLE PULSING AND BISTABILITY

Numerical simulation

Multiple pulsing with strong bistability is a usual operation state of passively mode-locked fiber laser. Such a phenomenon has been observed in fiber lasers mode-locked by SESAM, NPR or NOLM, independent of the exact mode-locking mechanism [144]. Therefore, the general expression as (3.12) can be used to model the saturable absorber in the numerical model.

It has been reported that the spectral filtering in the laser cavity induces multiple pulsing [116, 141, 143]. In the passively mode-locked fiber laser, the spectral filtering effect comes from two mechanisms: the gain dispersion and the cavity spectral loss. In EDF lasers, the gain dispersion can provide enough strong pulse shaping mechanism due to its relatively narrow gain bandwidth which is typical around 20~30 nm. In Yb-doped fiber laser, since the gain bandwidth is much broader, an extra spectral filter is required. For multiple pulsing phenomenon, the function of the gain filtering and the cavity spectral loss are equivalent [141]. Therefore, an extra spectral filter is used in the laser cavity and gain filtering effect is neglected to simplify the numerical model. The central wavelength of the filter is at 1550 nm.

The ANDi-laser shown in Figure 5.1 is investigated.

The laser is comprised of DCF which has -100 ps/nm/km dispersion and 6 W/km nonlinear coefficient. The gain of the laser is provided by 1 m EDF which has the same dispersion and nonlinear parameter to the DCF. The saturation energy of the EDF was $E_{sat} = 1$ nJ. Typically, a passively mode-locked fiber laser has repetition rate between 10 MHz~100 MHz, which corresponding to 1~20 m cavity length. In

the simulation, a simple model by considering a laser cavity of 2 m length which comprised of 1 m EDF and 1 m DCF is used. Therefore, the net dispersion is -0.2 ps/nm.

Figure 5.1 Schematic of the all-normal dispersion mode-locked fiber laser

In the simulation, the loss of the fiber and connection loss is neglected. The output coupler output 50% intensity so that the linear cavity loss is 3 dB.

Mode-locking can be self-started and stabilized when the gain is increased above 1.0. Figure 5.2 shows the intensity profile of the pulse in the temporal domain and the frequency domain while the gain values are set to 1.0, 1.5 and 2.0 respectively. By increasing the gain, pulse with higher energy and broader bandwidth can be achieved.

Figure 5.2 The evolution of (a) the pulse temporal profile and (b) the pulse spectrum with increasing gain

However, the bandwidth and the pulse energy can not be increased infinitely by increasing the gain. Figure 5.3 shows the pulse evolution in temporal domain when the gain is increased from 1.7 to 1.8. A new pulse is generated and then shares the net gain, thus reducing the peak power, the bandwidth and the energy of the pulse.

Figure 5.3 Simulation result for multiple pulse generation

Figure 5.2(a) shows the bandwidth evolution with gain. Self-started mode-locking can be achieved when $g_0 > 1.0$. The bandwidth increases with the gain until $g_0 = 1.7$. When the gain is increased to 1.8, the second pulse is generated and the bandwidth drops from 11 nm to 8 nm. Then, the bandwidth again increases with g_0 , until g_0 reaches 2.6, when a third pulse is generated and bandwidth drops again. In the simulation, the maximum bandwidth is limited to below 11 nm due to the new pulse generation. Figure 5.4(b) shows that the pulse energy is also limited below 1.1 nJ due to the multiple-pulsing effect.

When the gain is decreasing, the number of the pulses reduces. The pulse bandwidth and the pulse energy exhibit strong bistability to the gain variation, as shown in Figure 5.5.

Figure 5.4 Evolution of the (a) pulse bandwidth and the (b) pulse energy according to the gain

Figure 5.5 Bistability of the (a) pulse bandwidth and the (b) pulse energy according to the gain

Although the spectral filtering in the laser cavity has been confirmed as a mechanism of multiple pulsing, the dynamics of multiple pulsing is not fully understood yet.

To give a detailed view on the process of multiple-pulsing effect, a logarithmic scale for the pulse intensity is used to give a more detailed view on multiple pulse generation. In the logarithmic scale, the background CW noise can be examined. When the laser is stably mode-locked, the CW noise is suppressed. Increase of gain doesn't affect the CW noise. When the gain is increased to 1.7, it can be noticed that

CW light is amplified, as shown in Figure 5.3. When the CW noise is increased to a certain level, the new pulse emerges. The two pulses have almost the same peak power and pulse width. After the second pulse is formed, the CW noise is then suppressed and two pulses can be kept stable in the laser cavity. In the simulation, the generation of a new pulse is always accompanied by an amplification of the CW noise.

*Figure 5.6 Simulation result of the multiple pulses generation
(Logarithmic scale)*

It is well known that self-starting mode-locking is initiated by the intensity dependent cavity loss which is provided by the saturable absorber [88, 89]. The mode-locked pulse can be formed out of the background noise which is randomly fluctuating intensity. As the saturable absorber induces lower loss to higher intensity, the CW light with low intensity is suppressed and the pulses can be built up from some random spikes after many cavity round-trips. Therefore, the pulse self-starting shall be supported by the priority of the mode-locked pulse over the CW light in the

gain competition. Hence, the loss for the CW light must be always higher than the loss for the pulses to sustain the mode-locking. On the contrary, when the loss for CW light is lower than that of the pulses, the CW light is amplified thus inducing the multiple pulsing, as shown in Figure 5.6.

Net cavity loss in the passively mode-locked fiber laser is mainly contributed by three factors: the nonlinear loss caused by saturable absorber, the loss caused by the spectral filter and the linear loss caused by the fiber or the insertion loss of the components. Normally, the net loss of the CW light is decided by the linear net loss and always has a fixed value while the net loss for the pulses varies due to the nonlinear components.

As shown in Figure 5.2, by increasing the gain, the mode-locked pulse will have higher pulse energy, and broader pulse bandwidth as well. When there is a spectral filter in the laser cavity, the broader the pulse bandwidth, the higher loss would be induced to the pulse. Therefore, the spectral filter always provides negative feedback to the mode-locked pulses.

Figure 5.7 Nonlinear loss of the mode-locked pulse with increasing gain

Such negative feedback can be confirmed by the simulation. The loss of the laser cavity and the loss of each nonlinear device are shown in Figure 5.7. With the increasing gain, the loss of the saturable absorber decreases due to stronger saturation, which corresponding to a positive feed back; the loss of spectral filter increases almost linearly due to the broader pulse bandwidth and induces negative feedback. The total cavity nonlinear loss doesn't change much when the gain is increased from 1 to 1.1, after that, the total nonlinear loss to the pulse is dominated by the loss of the filter, and increases with the increasing gain. When the gain is increased above 1.7, the total cavity nonlinear loss is above 0.2, which equals to maximum loss of the saturable absorber. The net loss of the mode-locked pulse becomes equivalent to the net loss of the CW light, so that the CW light is no longer suppressed. A new pulse then can be generated when the CW light is amplified above the threshold of mode-locking. Once the new pulse is formed, the pulses share the net gain and the pulse

bandwidth decreases, and the mode-locked pulses take the priority in the gain competition again and the two pulses operation can be stabilized.

The new pulse is generated when the bandwidth and the nonlinear loss are maximized at the value which is equal to the loss of the CW light. Therefore, the mechanism of the multiple-pulsing effect actually is the gain competition between the mode-locked pulse and the CW light.

From the simulation result, it reveals that the gain competition is also the mechanism of the bistability. Figure 5.8 shows variation of the cavity nonlinear loss with the pulse bandwidth.

When two or more pulses with maximized bandwidth is stabilized in the laser cavity and the gain decreases, firstly the nonlinear loss of the mode-locked pulse is dominated by the spectral filter, and decreases with decreasing pulse bandwidth, as shown in Figure 5.8. The pulse with lower energy and narrower bandwidth always has lower net loss. If there is any fluctuation on the two pulses, the pulse with lower energy would be amplified in prior to the pulse with higher energy, and the two pulses can be stabilized. The decreasing of the gain will not reduce the pulse number in this case, but reduce the energy and the bandwidth of all the pulses.

Figure 5.8 Nonlinear loss of the mode-locked pulse with different bandwidth

When the pulse bandwidth is reduced to below 4 nm, the nonlinear loss of the laser is dominated by the saturable absorber, and the cavity feedback becomes positive. The pulse with lower energy and narrower bandwidth has lower net loss, as shown in Figure 5.8. While there is random disturbance to the two pulses and induces energy imbalance between the pulses, the pulse with lower energy would be suppressed, and the pulse with higher energy will be amplified due to the gain competition. Therefore, the low energy pulse vanishes and the pulse number reduces. Therefore, the mechanism of the reduction of the pulse number can be attributed to the gain competition between the pulses, and the pulse number drops when the laser cavity has minimum nonlinear loss.

Figure 5.9 Bistability of the pulse number according to pulse bandwidth

The simulation result shown in Figure 5.9 confirms the analysis, in which the two pulses keep stable when the bandwidth is larger than 4 nm and reduce to single pulse when the bandwidth is less than 4 nm.

In summary, it is confirmed here that multiple pulses formation is actually caused by the gain competition between the pulse and the CW noise. The spectral filter acts as a “bandwidth clumper” and provides negative feedback to the laser. When the positive feedback of the saturable absorber is compensated by the spectral filter, multiple pulses can be formed. The new pulse is generated when the laser cavity has maximum nonlinear loss. Since the pulse number reduces when the laser cavity has minimum nonlinear loss, strong bistability can be observed.

Bandwidth & pulse energy limitations

Since broad bandwidth is always required to achieve short pulses, and broader pulse bandwidth in the same laser cavity always corresponds to higher pulse energy [32, 46], it's necessary to understand the mechanism of bandwidth limitation in the ANDi-lasers. However, to the best of our knowledge, no theoretical investigation on this point has been reported at present.

Based on the mechanism of multiple pulsing which is analyzed in the last section, analytical investigation on the bandwidth limitation based on Gaussian pulse approximation is demonstrated here.

To be general, it can be assumed that the filter has a Gaussian spectrum and assume the pulse spectrum of mode-locked pulse is also Gaussian when it transmits through the filter. The pulse shall have the same central wavelength to the filter. The Gaussian pulse in frequency domain can be written as

$$\tilde{A}(\omega) = \tilde{A}_0 \exp\left(-\frac{\omega^2}{2\Omega_p^2}\right) \quad (5.1)$$

where $\tilde{A}_0$ is the pulse amplitude in the frequency domain, ω is the optical frequency deviation from the optical carrier, Ω_p is the pulse bandwidth. The pulse energy is:

$$E_p = \int_{-\infty}^{\infty} \tilde{A}_0^2 \exp\left(-\frac{\omega^2}{\Omega_p^2}\right) d\omega = \tilde{A}_0^2 \Omega_p \sqrt{\pi} \quad (5.2)$$

The filtering function of the spectral filter can be written as

$$\tilde{A}'(\omega) = \tilde{A}(\omega) \exp\left(-\frac{\omega^2}{2\Omega_f^2}\right) \quad (5.3)$$

where Ω_f is the bandwidth of the spectral filter.

The pulse energy of the Gaussian pulse after the filter can be written as:

$$E_f = \int_{-\infty}^{\infty} \tilde{A}_0^2 \exp\left(-\frac{\omega^2}{\Omega_p^2}\right) \exp\left(-\frac{\omega^2}{\Omega_f^2}\right) d\omega = \sqrt{\pi} \tilde{A}_0^2 \frac{\Omega_p \Omega_f}{\sqrt{\Omega_p^2 + \Omega_f^2}} \quad (5.4)$$

Then the loss of the filter is

$$l_F = 1 - E_f / E_p = 1 - \frac{\Omega_f}{\sqrt{\Omega_p^2 + \Omega_f^2}} \quad (5.5)$$

For CW light with central frequency located at the central wavelength of the spectral filter, the net loss is

$$l_{CW} = 1 - (1 - l_0)(1 - l_{lm}) \quad (5.6)$$

where l_{lm} is the linear loss of the laser cavity. The net loss for the optical pulse is

$$l_p = 1 - (1 - l_F)(1 - l_{lm})(1 - l_s) \quad (5.7)$$

where l_s is the loss of saturable absorber.

For stable mode-locking, the net loss for the pulse must be smaller than the loss for the CW light, otherwise a new pulse may be form. Therefore, the condition for stable single-pulse mode-locking is:

$$l_p < l_{CW} \quad (5.8)$$

By substituting equation (5.6) and (5.7) to(5.8), the condition for single pulse mode-locking can be achieved, which is

$$\Omega_p < \Omega_f \sqrt{\frac{(1-l_s)^2}{(1-l_0)^2} - 1} \quad (5.9)$$

For the case that the pulse peak power is much higher than the saturation power of the saturable absorber, the nonlinear loss of the saturable absorber can be neglected, then achieve

$$\Omega_p < \Omega_f \sqrt{\frac{1}{(1-l_0)^2} - 1} \quad (5.10)$$

Form (5.10) gives the bandwidth limitation of the ANDi-laser. The result reveals that the maximum bandwidth of the soliton is not only affected by the spectral filter, but also affected by the modulation depth of the saturable absorber. This result can be a good explain to the experiment report on the ANDi-laser in [32], in which the pulse number in the laser cavity can be changed by adjusting the saturable absorber.

To verify the analytical model, the simulation results of maximum bandwidth and the analytical results are compared, as shown in Figure 5.10.

Bothe the numerical model and the analytical result are used to calculate the maximum bandwidth that can be achieved in the laser cavity according to different modulation depth and keep other parameters unchanged. It shows that the analytical result fits the numerical simulation very well. The small deviation between the analytical result and the simulation result is mainly caused by the Gaussian approximation for the pulse spectrum. In simulation, pulse spectrum can deviate from Gaussian profile, as shown in Figure 5.11.

Figure 5.10 The maximum bandwidth achievable at different modulation depth

Figure 5.11 Optical spectrum of the pulse with maximized bandwidth when the modulation depth is 0.5

In summary, bandwidth limitation of the mode-locked pulse in the ANDi-laser is investigated. The maximum achievable bandwidth depends on both the cavity spectral loss and the modulation depth of the saturable absorber. The results show that broader bandwidth and higher pulse energy can be achieved by increasing the modulation depth of the saturable absorber, as shown in Figure 5.10 and Figure 5.12.

The result shall be useful for the designing of the passively mode-locked fiber lasers with all-normal dispersion laser cavity.

Figure 5.12 The maximum pulse energy achievable at different modulation depth

5.3. WAVE-BREAKING IN ALL-NORMAL-DISPERSION PASSIVELY MODE-LOCKED FIBER LASERS

As shown in the previous section, the negative feedback of the spectral filter can induce multiple pulsing operation of the ANDi-laser. Here is still a question that: will multiple pulses always be formed by increasing the gain?

It was indicated that when the bandwidth is narrow enough, for example, 10 nm, multiple pulses shall always be able to be formed with enough gain in Ref [141]. However, in some experiments have been reported, multiple pulsing was not observed even with a narrow bandwidth spectral filter [44]. Therefore, to achieve higher energy and broader bandwidth mode-locked pulse, a more comprehensive investigation on the stability of the mode-locking is required. In this section, the

properties of the mode-locked pulses according to different net dispersion are investigated theoretically.

Numerical simulation

Figure 5.13 The maximum pulse energy achievable at different cavity length

Figure 5.14 Pulse width at different cavity length when the pulse energy is maximized

The numerical model is used to investigate the maximum pulse energy and pulse bandwidth that can be achieved in an ANDi-laser with varying net dispersion.

The modulation depth of the saturable absorber is set to be 0.4. The net dispersion of the laser cavity is varied by changing the length of the DCF (L_{DCF}) in the laser cavity.

Figure 5.13 shows the maximum pulse energy achievable in the laser cavity when L_{DCF} increases. It reveals that the increasing of L_{DCF} is an efficient method to increase the pulse energy. Longer laser cavity also induce stronger chirp to the mode-locked pulse, and the pulse is stretched longer in temporal domain, as shown in Figure 5.14. The result is agreed with Akhmediev *et al*'s result that larger net dispersion leads to higher pulse energy [93].

Figure 5.15 The maximum bandwidth achievable at different cavity length

As introduced in Chapter 2, the chirped pulses from the ANDi-laser should be able to be compressed to nearly transform limited pulse. The compressed pulse width is dominated by the bandwidth of the mode-locked pulse. Figure 5.15 shows the maximum pulse bandwidth which can be achieved at different DCF length.

When the cavity length is less than 7 m, the achievable maximum bandwidth almost doesn't change, and the bandwidth is limited by multiple pulsing phenomenon. The simulation result agrees with the analysis in (5.10) which indicates that the multiple-pulsing limited bandwidth is fixed in a laser with fixed modulation depth.

When the laser cavity is longer than 7 m, the maximum achievable bandwidth reduces with increasing cavity length. The pulse energy limitation also changes. Instead of generating new pulses, the stable mode-locked pulse evolves into noise-like emission due to the wave-breaking effect when the gain is increased.

Figure 5.16 The pulse spectrum at different gain when the length of the DCF is 20 m

Firstly noisy sidebands are generated in the optical spectrum when the gain increases, as shown in Figure 5.16, then the pulse breaks into noise-like pulses with broad bandwidth and fluctuating temporal profile, as shown in Figure 5.17. The result reveals that multiple-pulsing is not a necessarily phenomenon in the ANDi-laser even

in laser cavity has strong spectral filtering effect. The wave-breaking effect takes over multiple-pulsing effect when the net dispersion is large [145].

Figure 5.17 (a) Temporal profile and (b) optical spectrum of the noise-like pulse; $g_0 = 16$ and the length of the DCF is 20 m

Figure 5.18 The maximum peak power achievable at different cavity length

Wave-breaking is an effect of over-taking the red-shift and the blue-shift light in nonlinear fiber with normal dispersion. It can generate sidebands on the pulse wings in both temporal domain and frequency domain, and lead to instability of mode-locking. The weak-breaking condition has been given in ref [145]. To guarantee

wave-breaking free operation, the peak power pulse should be inversely proportional to the square of the fiber length. Figure 5.18 gives the maximum intra-cavity peak power achievable at different cavity length. It shows that for longer L_{DCF} , the mode-locked pulse breaks into noise-like emission at lower peak power.

Discussions

Therefore, there are two mechanisms limiting the pulse energy and the pulse bandwidth in the ANDi-laser: the multiple pulsing and the wave-breaking effect. When $L_{DCF} < 7m$, the limitation of the pulse energy and the pulse bandwidth is dominated by multiple-pulsing effect. Since the bandwidth limitation is decided by the modulation depth and the spectral filter, maximum bandwidth and the maximum peak power changes little while the maximum pulse energy is increased from 1 nJ to 5 nJ.

When the length of the DCF is further increased, the threshold of the noise-like emission decreases. The laser instability is then dominated by the wave-breaking effect. The maximum bandwidth decreases with increasing of the DCF length due to the decreasing of the wave-breaking threshold.

Therefore, there is a best value for L_{DCF} to achieve maximum pulse energy without decreasing the pulse bandwidth.

5.4. EXPERIMENT ON CAVITY OPTIMIZATION

To verify the theoretical prediction, an ANDi-laser mode-locked by NPR mechanism is investigated experimentally. The experiment setup is shown in Figure 5.19.

In the laser cavity, 5 m highly doped (2000 ppm) EDF with -20 ps/nm/km dispersion is used to provide the necessary gain for high pulse energy. A fiber bench with wave plates and polarizer mounted on it is used to mode-lock the laser by NPR technique. Two segments of DCF with -96 ps/nm/km dispersion are used in the laser cavity to provide large normal net dispersion. DCF2 with a fixed length of 2.9 m is put right after the fiber bench. DCF2 is located after the EDF. By changing the length of DCF2, the net dispersion of the laser cavity can be modified. The laser is pumped by a 1 W laser diode at 1480 nm central wavelength. A 50/50 output coupler is used.

Figure 5.19 (a) Setup & (b) schematic of the ANDi-laser

As introduced in Chapter 4, the modulation depth of the NPR can be adjusted by changing the orientation of the wave plates. This allow us to investigate the pulse dynamics under different saturable absorption while keep the other parameters unchanged.

Firstly, 2 m length of DCF (DCF1) is employed in the laser cavity. The fundamental repetition rate is 11.5 MHz. Mode-locking can be achieved by adjusting the orientation of the wave plates and the polarizer. The mode-locked pulse shows

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typical spectrum property of the mode-locked pulse in normal net dispersion laser cavity which has steep edges. The pulse bandwidth varies according to the orientation of the wave plate and the pump power.

By correctly setting the wave plates and the pump power, mode-locked pulses with maximum bandwidth can be achieved. The bandwidth between the two steep edges is 15.1 nm, as shown in Figure 5.20(a). At this state, the maximum pulse energy of 2.1 nJ is also achieved, with an average output power of 24 mW. The FWHM of the autocorrelation trace of the pulse is 22 ps, as shown in Figure 5.20(b).

Adjusting the wave plates leads to multiple pulsing in the laser cavity and reduces the pulse bandwidth. A maximum of 3 pulses can be achieved in this condition by adjusting the wave plates, as shown in Figure 5.21. It reveals that the properties of the saturable absorber significantly affect the maximum bandwidth and the maximum pulse energy of the mode-locked pulses.

Figure 5.20 (a) Optical spectrum and (b) autocorrelation trace of the pulse when the length of the DCF is 2 m

Figure 5.21 Oscilloscope trace of (a) single pulse (b) three pulse operation

Then the length of the DCF is increased to 4 m. The fundamental repetition rate is now 10.3 MHz. Mode-locking can be self-started when the pump power is 160 mW. The maximum bandwidth between the two steep edges is 15.02 nm when pump power is 240 mW, as shown in Figure 5.22(a). The maximum pulse bandwidth is almost the same to the one with 2 m DCF. The average power is 54 mW, which corresponds to 5.3 nJ pulse energy. The pulse width is significantly increased and exceeds the scanning range of the autocorrelator, as shown in Figure 5.22(b). The adjustment of the wave plates or increase of the pump power will also lead to multiple pulsing in the laser. The result verifies the theoretical prediction that when the laser instability is dominated by the multiple-pulsing effect, increasing of the length of the DCF can efficiently increase the pulse energy without affecting the maximum bandwidth.

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Figure 5.22 (a) Optical spectrum and (b) autocorrelation trace of mode-locked pulse with 4 m DCF

By increasing the length of the DCF to 6 m, the maximum bandwidth decreases, as shown in Figure 5.23(a). The self-start mode-locking threshold is 185 mW pump power at this time and the maximum pulse energy is 7.3 nJ when the pump power is 290 mW. The pulse width becomes larger. Monitored by a high-speed 45 GHz photo detector and 50GHz sampling oscilloscope, the pulse width is 110 ps. The maximum bandwidth achieved is 11 nm, which is significantly reduced due to the increase of the DCF length. Further increasing the gain will lead to noise-like emission of the laser and multiple pulsing is not observed. Figure 5.23(b) shows that the optical spectrum evolves to the noise-like emission when the gain is increased. Noisy sidebands emerge in the optical spectrum with the increasing gain and finally collapse into noise-like pulses, as shown in Figure 5.24(a). Although the pulse width is much larger than the scanning range of the autocorrelator, the autocorrelation trace still shows typical property of the noise-like emission which is a sharp peak located on a broad pedestal [120], as shown in Figure 5.24(b).

Figure 5.23 Optical spectrum of the (a) stable mode-locked pulse with 200mW pump power and the (b) mode-locked pulse with side band when pump power is 280mW

Figure 5.24 (a) Optical spectrum and (b) autocorrelation trace of the noise-like pulse with 6m DCF employed in the laser cavity

The experimental results agree well with the theoretical analysis. When the laser cavity length is short, multiple pulsing dominates the pulse energy limitation. In this condition, the maximum bandwidth of the mode-locked pulse would not be affected by the length of the DCF and higher pulse energy can be achieved by employing longer DCF in the laser cavity. In the experiment, maximum 5.3 nJ pulse

can be achieved without decreasing the bandwidth of the pulse. Further increase the laser cavity length, pulse energy can be further increased by sacrificing the pulse bandwidth.

Figure 5.25 Supercontinuum generated by the 7.3 nJ pulse

To test the high energy pulse achieved, it is launched into 60 m length of high nonlinear fiber (HNLF). Over 800 nm bandwidth supercontinuum is achieved. As shown in Figure 5.25.

5.5. WAVELENGTH SWITCHING DUE TO THE COMPLEX FILTERING EFFECT

The spectral filter in the ANDi-laser is particularly important for its strong pulse shaping ability. It's also a key factor for multiple pulsing. At present, most theoretical investigation on the ANDi-laser supposed that the filter had a Gaussian or Lorentzian lineshape which was an ideal approximation for the practical systems.

In the EDF ANDi-laser, in most case, the spectral filtering effect is provided by the gain dispersion. The GLE which is widely used to study mode-locked laser assumes a Lorentzian gain lineshape. However, in practical, the spectral gain shape of the EDF is much more complex.

Figure 5.26 ASE of the EDF

Figure 5.26 shows the typical amplified simulated emission (ASE) of the EDF. There are two emission peaks in the spectrum, located at 1530 nm and 1560 nm, respectively. Therefore, a more practical theoretical model is required.

Theoretical analysis

Here consider an ANDi-laser mode-locked by NPR. As have shown in Chapter 4, the fiber birefringence together with a NPR can form a Lyot filter and provide a periodical filtering effect. Normally, such a filtering effect is weak and can be neglected when there is no high birefringence fiber in the laser cavity. However, together with the dual-peak gain spectrum, the Lyot filter may lead to complex

wavelength dynamics by adjusting the wave plates [146]. Therefore, a vector form of the GLE should be employed to include the fiber birefringence [142].

$$\begin{aligned} \frac{\partial u}{\partial z} = & +i\beta u - \delta \frac{\partial u}{\partial T} - \frac{i\beta^*}{2} \frac{\partial^2 u}{\partial t^2} + i\gamma \left(|u|^2 + \frac{2}{3}|v|^2 \right) u + \frac{i\gamma}{3} v^2 u^* \\ & + \frac{g}{2} u + \frac{g}{2\Omega_s^2} \frac{\partial^2 u}{\partial t^2} \end{aligned} \quad (5.11)$$

$$\begin{aligned} \frac{\partial v}{\partial z} = & -i\beta v + \delta \frac{\partial v}{\partial T} - \frac{i\beta^*}{2} \frac{\partial^2 v}{\partial t^2} + i\gamma \left(|v|^2 + \frac{2}{3}|u|^2 \right) v + \frac{i\gamma}{3} u^2 v^* \\ & + \frac{g}{2} v + \frac{g}{2\Omega_s^2} \frac{\partial^2 v}{\partial t^2} \end{aligned} \quad (5.12)$$

$$g = \frac{g_0}{1 + \frac{E}{E_s}} \quad (5.13)$$

where u and v are the two normalized slowly varying pulse envelopes along the slow and the fast axes of the fiber respectively. $2\beta v = \frac{2\pi\Delta n}{\lambda}$ is the wave-number

difference, $2\delta = \frac{2\beta\lambda}{2\pi c}$ is the inverse group-velocity difference along the two axes.

β^* is the dispersion parameter and γ is the nonlinearity coefficient of the fiber. g_0 is the small signal gain, Ω_s is the gain dispersion, ω is the optical frequency shift from the central gain, g is the saturated gain, E is the pulse energy, and E_s is the saturation energy of the gain fiber. Increasing the value of g_0 is physically equivalent to increasing the pump power in the experiment.

To investigate the laser with dual-peak gain medium, The GLE shall be modified and the fourth order gain dispersion shall be included. Equation (3.7) shall be modified to[147]:

$$g(\omega) = \frac{g_0}{1 - (\omega - \omega_0)^2 T_2^2 + (\omega - \omega_0) T_2^4} \quad (5.14)$$

The modified GLE is known as the Swift-Hohenberg equation (SHE) [147]. By setting the central wavelength at 1545 nm, and $T_2 = 200 \text{ fs}$, the gain profile with two peaks located at 1530 nm and 1560 nm can be achieved, as shown in Figure 5.27.

Figure 5.27 Gain profile of the SHE

The SHE is numerically solved by split-step Fourier method. By simply setting $g_0 = 0$, the SHE becomes the coupled NLE and can be used to model pulse propagation in the un-doped fiber.

In the simulation, the laser includes 5 m EDF, 5 m dispersion shifted fiber (DSF), 5 m DCF and NPR the part. The dispersion of each fiber section is -20 ps/nm/km, -1 ps/nm/km and -96 ps/nm/km respectively; and the nonlinear coefficient of each fiber section is 6 W/km 3 W/km and 3 W/km respectively. To be

general, the beat length of the fiber is set to be $1/5$ of the total cavity length. The NPR in the numerical model includes a polarizer which oriented α from the fiber's fast axis and wave plate with phase delay ϕ between its two axes. The orientation of the fast-axis of the wave plate is θ to the fiber's fast axis. Note that changing the value of ϕ , α , θ is physically equivalent to changing the orientations of the wave plates in the experiment. By carefully setting the value of ϕ , α and θ , the NPR can form an artificial saturable absorber.

Figure 5.28 (a) Optical spectrum and (b) temporal profile of the pulse mode-locked at 1530 nm central wavelength

When $\phi = 0.3$, $\alpha = 5\pi/8$, $\theta = 1\pi/8$ and $g_0 = 2$, stable mode-locking can be achieved with 1530 nm central wavelength, as shown in Figure 5.28.

The FWHM of the pulse is 35 ps, the 3 dB bandwidth is 12 nm. The simulation result shows that the pulse shifts to the left side of the time window after each roundtrip, as shown in Figure 5.29. It reveals that the group velocity of the pulse is slower than the normalized velocity. The roundtrip time has 8 ps difference between the pulses at different wavelength.

Figure 5.29 Location of the mode-locked pulse at 1530 nm central wavelength in the time window at different roundtrips

By changing the linear phase delay to $\phi = 1.9$, the mode-locking wavelength can be switched to a 1530 nm central wavelength, as shown in Figure 5.30. The pulse has also 35 ps pulse width and 12 nm bandwidth. In this occasion, the pulse travels faster than the normalized velocity with 8 ps per-roundtrip, as shown in Figure 5.31. Therefore, the mode-locked pulse shall have higher repetition rate at 1560 nm than at 1530 nm.

The simulation results show that the dual-peak gain profile can lead to wavelength switching in a NPR mode-locked fiber laser by adjusting the wave plates. Each of the two peaks of the gain acts as distinct spectral filter respectively, and the mode-locked pulse can be shaped by each filter.

Figure 5.30(a) Optical spectrum and (b) temporal profile of the pulse mode-locked at 1560 nm central wavelength

Figure 5.31 Location of the mode-locked pulse at 1560 nm central wavelength in the time window at different roundtrips

Experiment

The laser setup is shown in Figure 5.32. a 6 m length of EDF with -20 ps/nm/km dispersion is used as the gain medium of the laser, 6 m DCF with -96 ps/nm/km dispersion is used to provide large normal net dispersion. All the

pigtails of the components are made of DSF whose zero dispersion wavelength is around 1560 nm.

Figure 5.32 Setup of the passively mode-locked fiber laser with wavelength switching effect

By appropriately adjusting the orientation of the wave plates, self-start mode locking of the laser can be achieved at 1532 nm and 1560 nm central wavelengths respectively. One central wavelength can be switched to the other by adjusting the wave plates. Figure 5.33 shows the optical spectrum and the temporal profile of the pulse at 1560 nm. The pulse width exceeds the range of the autocorrelator and a high speed oscilloscope is used to monitor the temporal profile of the pulse. At this wavelength, the self-start mode-locking threshold is 248 mW pump power. The laser is fundamentally mode-locked until the pump power is increased to 281 mW, above which multiple pulsing is observed. When the pump power is 280 mW, the laser is fundamentally mode-locked with 11.585 MHz repetition rate, the output power is 24.1 mW and the calculated pulse energy is 2.1 nJ. The bandwidth between the two steep edges is 13 nm. As shown in Figure 5.33(b), the pulse width is 100 ps. By

adjusting the wave plates and the polarizer, the central mode-locking wavelength can be switched to 1532 nm. At 1532 nm, the laser has a mode-locking threshold of 148 mW and can be fundamentally mode-locked with pump power below 160 mW. With 160 mW pump power, the fundamental repetition rate is 11.582 MHz which is 3 kHz lower than the 1560 nm pulse. It shows that the pulse at 1532 nm has 22 ps time delay per-roundtrip relative to the pulse at 1560 nm. The average output power is 8.8 mW, corresponding to 0.76 nJ pulse energy.

Figure 5.33 (a) Optical spectrum and (b) oscilloscope trace of the pulse at 1560 nm central wavelength

Figure 5.34 (a) Optical spectrum and (b) autocorrelation trace of the pulse at 1532 nm central wavelength

Figure 5.35 Autocorrelation trace of the de-chirped pulse at (a) 1532 nm central wavelength (b) 1560 nm central wavelength

As shown in Figure 5.34, the bandwidth between the two steep edges is around 11 nm and the FWHM width of the pulse autocorrelation trace is 24 ps.

The mode-locked pulse at each central wavelength can be de-chirped by launching the attenuated pulse into standard SMF with anomalous dispersion. Attenuation is necessary to avoid fiber nonlinearity induced phase shift in the SMF. After de-chirping, the 1532 nm pulse is compressed to 1.1 ps and the 1560 nm pulse is compressed to 850 fs, as shown in Figure 5.35.

In order to check if such wavelength switching of mode-locking is a generic feature of the laser oscillator, I deliberately change the cavity property of the laser by adding 4m, 8m, 10m DCF into the laser cavity and changing the experiment components. The wavelength switching between the two central wavelengths can still be observed.

Discussion

The experiment shows that the pulses at 1560 nm have higher pulse energy and broader pulse width, while the bandwidth of the pulses at the two wavelengths are almost the same. This is different to the simulation result in which the pulse width at

the two wavelengths are the same. This difference comes from the model which is based on the SHE. In the SHE, the gain spectrum is perfectly symmetric, and forms two spectral filters with equal bandwidth. In practical, the gain spectrum is asymmetric. The spectral filter at 1560 nm has broader bandwidth. According to (5.9), mode-locking with broader bandwidth can be achieved.

Except for the pulse bandwidth, the experimental results are in good agreement with the numerical simulation. Both in the simulation and the experiment wavelength switching between the two distinct gain peaks is observed. The mode-locked pulse train has different repetition rate at each wavelength due to the large net dispersion. The mode-locking wavelength is decided by the orientation of the wave plates and the polarizer.

In the NPR mode-locked laser, a weak spectral filtering effect can be formed due to the fiber birefringence. By adjusting the wave plates, the wavelength of the peak transmission can be shifted. Laser emission can be achieved when the peak transmission wavelength superposes with the gain peak.

In the ANDi-laser the pulse is strongly chirped and a bandwidth filter can cut the pulse wings with low intensity and provide strong saturable absorption. For the fourth order gain dispersion, the convex between the two gain peaks can not provide such pulse shaping mechanism. Therefore, the pulse shaping is provided by the two gain peaks which act as two BPFs independently. Unlike in the anomalous dispersion laser, in which pulse shaping mechanism is mainly provided by the balancing between the fiber nonlinearity and chromatic dispersion, dual-wavelength mode-locking is not observed in the ANDi-laser. Therefore, each gain peak can be treated as

an independent spectral filter. It reveals that with the complex gain profile of the EDF, the discussion in section 5.2 and section 5.3 is still applicable.

5.6. CONCLUSIONS

In this chapter, I investigated the dynamics of mode-locking in the ANDi-laser. It was confirmed that the spectral filter, which is the key component for pulse shaping in the ANDi-laser, could also act as a pulse energy clamper. The clamping effect would limit the pulse energy as well as pulse bandwidth by inducing multiple-pulsing effect. It was found that a new pulse could be generated while the net loss for the pulses reached a maximum value which equaled to the net loss of the CW light. The pulse number reduced when the net loss for the pulses was minima and generated strong bistability effect for multiple pulsing.

The limitation of the pulse bandwidth has been discussed. It is demonstrated that the maximum bandwidth of the pulse was actually decided by the bandwidth of the spectral filter and the modulation depth of the saturable absorber. This mechanism proposed that the parameters of the saturable absorber could be a factor to optimize the ANDi-laser design.

For a laser with a long cavity and large net normal dispersion, It is indicated that the wave-breaking effect became important and affects the stability of the mode-locking. Longer cavity with larger normal dispersion could increase the pulse energy but decrease the pulse bandwidth when the wave-breaking effect became the limitation of pulse energy. Therefore, an optimization on the cavity length could be applied to increase the pulse energy without decreasing the pulse bandwidth.

An experimental setup of NPR mode-locked, EDF ANDi-laser has been demonstrated. The experimental results verified the theoretical analysis and 5.3 nJ pulse with 15 nm bandwidth was achieved at 1560 nm central wavelength.

As the EDF has a dual-peak gain spectrum which is different to the Lorentzian approximation in the GLE, a more practical model based on the SHE was applied. The theoretical and experimental results indicated that the dual-peak actually functioned as two separated gain filter and shaped mode-locked pulse independently. A wavelength switching phenomenon due to the dual-peak gain was observed both in the simulation and in the experiment.

6 Low Repetition Rate Passively Mode-locked Fiber Laser System

6.1. INTRODUCTION

In the last Chapter, the effect of the spectral filter and the saturable absorber has been investigated. Since the gain bandwidth of EDF and the bandwidth of the mode-locked pulse are comparable, the spectral filtering effect will be always important for pulse shaping in EDF based laser. The nonlinear dynamics of the mode-locking makes it difficult to study the pulse shaping effect of the saturable absorber. Therefore, a YDF laser is investigated in this chapter.

YDF has been widely used as gain medium to construct a high-energy passively mode-locked fiber laser because of its wide gain bandwidth, high gain around 1060 nm and high saturation power. Compared to EDF, the gain spectrum of the YDF is much broader, and the gain filtering effect in a passively mode-locked YDF laser can be neglected. Furthermore, optical fiber normally has strong normal dispersion. These characteristics make it convenient to investigate the dynamics in passively

mode-locked fiber laser with all-normal-dispersion laser cavity in absent of the spectral filtering effect.

Previous research works show that the normal dispersion of optical fiber at 1060 nm impacts stable mode-locking in YDF lasers [148]. Ilday *et al.* proposed similariton passively mode-locked fiber laser which used intra-cavity grating pairs to compensate the normal dispersion. The similariton laser can generate mode-locked pulse with over 10 nJ pulse energy with around 20 MHz repetition rate. Recently, the ANDi-laser has been proposed. In such a laser, the spectral filter is essential for stable mode-locking. However, the requirement of dispersion compensation or spectral filter in the laser cavity breaks the all-fiber structure of the laser.

In this chapter, an all-fiber mode-locked laser system without any intra-cavity filter is demonstrated. The laser generates optical pulse train with repetition rate below 1 MHz.

Conventionally, such low repetition rate pulses are generated by Q-switched lasers [149]. Q-switched lasers can generate low repetition rate pulses (1~200 kHz) with a long pulse width (>10 ns). However, in many applications, such as fluorescence lifetime imaging measurements and high resolution LIDAR system, short pulse (ps~sub-ps) is required. Passively mode-locked lasers can be used to generate such short pulses (fs~ps) but their repetition rate is typically high (>10 MHz). Conventional techniques to reduce the repetition rate of mode locked lasers need to use a modulator driven by external electric signal as a pulse-picker. Such a the system configuration is complex and the power efficiency is low.

The most effective method to reduce the repetition rate of a mode-locked laser is to extend cavity length. Compared to conventional solid state lasers which require a

multiple-passing technique to construct a long laser cavity [138], fiber lasers have advantages in terms of simple structure, compact size, cost efficiency, and low maintenance. However, the long cavity induces high nonlinear phase shift to the optical pulse and leads to wave-breaking or multiple pulsing phenomena. Therefore, to reduce the nonlinear phase shift, the peak power of the pulse should be limited to a reasonable level in order to keep stable fundamental mode-locking. Previous investigations show that the pulse energy is low (~ 100 pJ) in such low repetition rate (1~2 MHz) passively mode-locked fiber lasers [117, 150].

The system addressed here is an YDF based laser which act as a master oscillator and an Yb-doped double cladding fiber (Yb-DCF) amplifier. A SESAM works together with the strongly chirped pulse and the nonlinearity induced spectrum broadening to stabilize the mode-locking. By increasing the cavity length of the laser, the pulse energy could be significantly increased. Depending on cavity length, wave-breaking-free pulse with 2.9 nJ $\sim$ 6.9 nJ pulse energy and 870 kHz~187 kHz repetition rate has been achieved from the master oscillator. Over 4 μ J pulse energy can be obtained after amplification.

6.2. LOW REPETITION RATE PASSIVELY MODE-LOCKED FIBER LASER

Experiment setup

In contrast to the previous chapters in which NPR mode-locking is used, a SESAM is used to mode-lock the laser here. For a long laser cavity, the saturation absorption of NPR can be easily overdriven and affected by the environment induced birefringence instability. [114]. However, a SESAM can provide stable saturable

absorption independent of cavity length. It can be a great advantage for passively mode-locked fiber laser with long cavity.

The modulation depth of the SESAM is $\Delta R = 20\%$, the saturation fluence is $\Phi = 120 \mu\text{J}/\text{cm}^2$, and the relaxation time constant is $\tau = 500 \text{ fs}$. The SESAM is coupled into the laser cavity through a circulator which has 20dB isolation from port 3 to port 1. The circulator also acts as an isolator which ensures a unidirectional propagation and suppresses undesired reflections. Laser gain is provided by single mode 4m YDF which has $7.5 \mu\text{m}$ mode diameter at 1060nm and 250dB/m unsaturated absorption at 976 nm. A 976 nm single mode laser diode is employed to pump the laser. Hi-1060 SMF is used to extend the length of laser cavity and provide pure normal dispersion. The Hi-1060 SMF has $6.5 \mu\text{m}$ mode diameter and -50ps/nm/km dispersion at 1060 nm wavelength. In the experiment, firstly 500 m Hi-1060 SMF is used. A PC is employed to adjust the polarization state of light propagating along the laser cavity.

Figure 6.1 Setup of the low repetition rate laser

Results and Discussions

Since there is no spectral filter in the laser cavity, the central emitting wavelength of the laser is dominated by the length of YDF. The re-absorption mechanism of the YDF shifts the emission light to longer wavelength with longer YDF [75]. By selecting 3.3m YDF, the central wavelength of the laser is around 1068nm.

Figure 6.2 Optical spectrum of the stable mode-locked pulse

The mode-locking can be self-started when the pump power is above 124 mW. The optical spectrum of mode-locked pulse with respect to the different output average power of laser is observed in the optical domain using an OSA with 0.01nm resolution, as shown in Figure 6.2. The central wavelength is 1068.76nm, while the optical bandwidth of the pulse can be increased from 0.256 nm to 0.292 nm by increasing the pump power from 124 mW to 128 mW. The corresponding average output laser power is increased from 1.4 mW to 1.7 mW.

After detection by a 40 GHz photo-detector, the temporal waveform is measured in the time domain using a 50 GHz sampling oscilloscope, as shown in Figure 6.3.

The measured pulse width is around 910 ps. The calculated pulse TB product is 52.73, which shows that the pulse is extremely chirped due to the strong cavity dispersion and the pulse should be able to be compressed external the laser cavity. The electrical spectrum of the pulse is measured using a 40GHz electrical spectrum analyzer, as shown in Figure 6.4.

Figure 6.3 Oscilloscope trace of the stable mode-locked pulse

Figure 6.4 RF spectrum of the stable mode-locked pulse

The laser is mode-locked at fundamental repetition rate of 397 kHz, and the corresponding pulse interval is 2.52 μ s. when the average output power is 1.7 mW, the calculated pulse energy of single optical pulse is around 4.3 nJ. The pulse energy has been increased over 20 times compared to previous investigations on low repetition rate passively mode-locked fiber laser. This increment is caused by the all-normal-dispersion structure of the laser cavity.

Figure 6.5 (a) Optical spectrum and the (b) oscilloscope trace of the unstable mode-locked pulse

However, the pulse energy is still limited by fiber nonlinearity and can't be further increased in the laser. If increase the pump power to 130 mW, mode-locking becomes unstable, as shown in Figure 6.5.

By adjusting the PC, stable mode-locking may be lost or shifted to another central wavelength. For example, Figure 6.6 shows another mode-locking state at 1068.30 nm central wavelength. The corresponding 3 dB bandwidth in this state is 0.557 nm and the pulse width is 690 ps. The sensitivity to polarization of the laser may be caused by the NPR in the long fiber spool. Since all the components in the laser cavity are polarization independent, the polarization dependent loss in the laser

cavity is negligible. Therefore, the NPR in the laser system cannot generate strong saturable absorption effect. Also, recent researches on vector soliton in passively mode-locked fiber lasers showed that even in a polarization independent laser cavity, PC can still significantly affect the mode-locking [151]. We believe this polarization instability can be solved by using polarization maintaining fiber based laser cavity.

Figure 6.6 By rotating the PC, the central wavelength of the mode-locked pulse may shift to 1068.3nm. (a) Optical spectrum (b) Oscilloscope trace of the wavelength shifted mode-locked pulse.

To further investigate the performance of the passively mode-locked fiber with extremely long laser cavity, the cavity length is changed from 200 m to 1100 m. Self-start mode-locking can still be observed. The PC is set to the place where the maximum bandwidth can be achieved. In this experiment, It is noted that the emission wavelength of the laser is also affected by the cavity length. The central wavelength intends to shift to shorter wavelength with the increasing cavity length when the YDF length is fixed, as shown in Figure 6.7. We believe that this type of wavelength shift is due to the higher cavity loss in longer laser cavity. The central wavelength shifts from 1073 nm to 1068 nm when the length of SMF is increased from 200 m to 1100 m. The pulse spectrum has steep spectral edge which is a typical property of

wave-breaking-free pulse in normal dispersion passively mode-locked fiber lasers. The 10 dB bandwidth of the pulse spectrum decreases from 0.91 nm to 0.63 nm and the FWHM of the pulse increases from 400 ps to 1000 ps. The experimental result shows that the pulse is extremely chirped by the strong net normal dispersion.

Figure 6.7 Optical spectrum and oscilloscope trace of the low repetition rate pulse according to different cavity length; L is the length of the Hi-1060 SMF

Figure 6.8 Oscilloscope of the pulse train with different cavity length; L is the length of the Hi-1060 SMF

Figure 6.9 Pulse peak power and pulse energy for different cavity length from the master oscillator

When the passively mode-locked fiber laser is fundamentally mode-locked, the repetition rates are 870 kHz, 387 kHz, 278 kHz and 187 kHz while the fiber lengths

are 200 m, 500 m, 700 m and 1100 m respectively. Figure 6.8 shows the pulse train for each repetition rate. The corresponding average powers are 2.5 mW, 1.8 mW, 1.4 mW and 1.2 mW, respectively. Figure 6.9 shows the calculated pulse energy and pulse peak power. For reducing the repetition rate, the pulse energies are 2.9 nJ, 4.6 nJ, 5.0 nJ and 6.9 nJ respectively, while the pulse peak powers are 7.2 W, 7.0 W, 7.1 W and 6.9 W respectively. The pulse energy and the pulse width increase significantly when the cavity length is increased, and the pulse bandwidth decreases.

The laser has a turn-key operation for self-start mode-locking and can keep stable for hours before intended interruption. It shows that mode-locking in all-normal dispersion passively mode-locked fiber laser with ultra-long laser cavity is robust even without intra-cavity dispersion compensation and spectral filter. However, a stable mode-locking operation can not be achieved when the cavity length is less than 50 m in the experiments.

The failure to achieve stable mode-locking in short laser cavity can be caused by two factors, the first is the Q-switch instability [152]. For mode-locked laser with ps pulse width, the pulse energy must be high enough to achieve stable mode-locking, as written in (6.1).

$$E_p^2 > E_{sat,L} E_{sat,A} \Delta R \quad (6.1)$$

where E_p is the pulse energy, $E_{sat,L}$ is the saturation energy of the gain medium, $E_{sat,A}$ is the saturation energy of the saturable absorber. In the passively mode-locked fiber laser with all-normal-dispersion cavity, the pulse energy decreases with the decreasing of cavity length. In a short laser cavity, the pulse energy can be too low to achieve stable mode-locking.

Furthermore, when a passively mode-locked fiber laser is stably mode-locked, the pulse must reproduce itself after each roundtrip. The broadening effect of the pulse bandwidth and the pulse temporal width must be balanced [153]. In the soliton laser and the dispersion managed soliton laser, the soliton mechanism provides the balancing. In the ANDi-laser, the spectral filter can narrow the pulse in the both temporal domain and the frequency domain hence balance the dispersion induced temporal broadening and the nonlinearity induced bandwidth broadening. However, in the experiment, there is no spectral filter to narrow the pulse in the frequency domain.

In this experiment, stable mode-locking can't be achieved when the fiber length is shorter than 50 m. It reveals that the long laser cavity helps to stabilize the mode-locking. Due to the strong chirp caused by the normal dispersion of fiber, the red-shifted light and blue-shift light will be located at leading edge and trailing edge of the pulse in the time domain. Compared to the center part of pulse, the pulse wings have much lower intensity. As the pulse width increases with the extending of cavity length, pulse width within the laser is much larger than the recovery time of the SESAM in the long cavity. The SESAM can be regarded as a fast saturable absorber and response according to the pulse intensity. When the pulse is reflected by the SESAM, the red-shift and blue-shift light with low intensity will have higher loss than that of the central frequency due to the nonlinear reflectivity of the SESAM. Therefore, the SESAM performs equivalently to a spectral filter for such strongly chirped pulse and balances the spectrum broadening effect induced by fiber nonlinearity.

Figure 6.10 investigates the filtering ratio of a saturable absorber for input Gaussian pulse with different chirp. The chirped Gaussian pulse can be written as:

$$U(0, T) = \exp\left(-\frac{(1+iC)}{2} \frac{T^2}{T_0^2}\right) \quad (6.2)$$

where U is the normalized electrical field of the pulse, C is the normalized pulse chirp. The saturable absorber has a modulation depth of 0.5, and the normalized saturation power is 1. The filtering ratio is defined as $R_F = B_o / B_i$, where B_o is the bandwidth of the pulse after the saturable absorber, B_i is the bandwidth of the initial pulse.

Figure 6.10 Filtering ratio of the saturable absorber to the pulse with different chirp

When the pulse is transform limited, $R_F > 1$ which means the pulse bandwidth is broadened by the saturable absorber. When the chirp increases, R_F decreases. For $C > 1.5$, the pulse bandwidth can be narrowed by the saturable absorber. It reveals the SESAM in the laser cavity can form filtering effect for pulses with large chirp. Note that such filtering effect is only applicable when C is larger than a certain threshold, and stable mode-locking can not be achieved in the short laser cavity in which the chirp is weak.

6.3. AMPLIFICATION

To further increase the pulse energy, the fiber amplifier shown in Figure 6.11 is employed. The amplifier is constructed by Yb-doped double cladding fiber with 7.0 μm core diameter and 210 μm clad diameter. The pump absorption in the fiber inner cladding is 0.85 dB/m. A 976 nm fiber coupled single emitter multimode pump diode with 4 W maximum output power is introduced into the Yb-DCF through a commercial fiber bundle.

Figure 6.11 The schematic of the laser system

Figure 6.12 Optical spectrum of the amplified pulse with strong ASE at 1530 nm when the length of the Yb-DCF is 3 m

Figure 6.13 Optical spectrum of the amplified pulse when the length of the Yb-DCF is 10 m; the ASE at 1530 nm is suppressed.

The length of the Yb-DCF must be optimized to increase the performance of the amplifier. As shown in Figure 6.12, the ASE at 1030 nm is strong when the length of the YDF is 3 m, hence reduce the efficiency of the amplifier. By increasing the length of the Yb-DCF to 10 m, due to the re-absorption mechanism of the Yb-DCF, the ASE

at 1030 nm is suppressed, and the pumping light at 976 nm is efficiently absorbed, as shown in Figure 6.13.

Without any pulse distortion, the average power can be amplified to 1.27 W, 1.05 W, 0.85 W, and 0.8 W according to different repetition rate pulse. The pump power is 3.4 W, 3.2 W, 3.1 W and 2.8 W respectively. The pulse energy is amplified to 1.4 μJ , 2.6 μJ , 3.2 μJ and 4.3 μJ respectively, as shown in Figure 6.14, with increasing SMF length. The maximum peak power of amplified pulses can be over 4 kW. Compared with conventional Q-switched fiber laser, mode-locked laser with the low repetition rate has the advantages of all-fiber structure, self-start operation and shorter pulse width with comparable pulse energy.

Figure 6.14 Peak power and energy of the pulse at different cavity length from the amplified laser system

The average power can be further increased by increasing the pump power, but the pulse will break-up due to wave-breaking effect when the pump power is further increased in the setup, as shown in Figure 6.15. As the wave-breaking effect is mainly

caused by fiber nonlinearity, higher pulse energy can be expected by applying large-mode area (LMA) YDF [154].

Figure 6.15 The wave-breaking effect induces noisy pulse spectrum when the pump power is 4 W

The stimulated Brillouin scattering (SBS) which is a key impact on fiber amplifiers in the laser system is not observed in the amplifier [155]. By monitoring the back scattering of the amplifier, and find that the back scattering of the amplifier is dominated by the ASE, the Rayleigh scattering of the pulse and the reflection of the splicing point between the Yb-DCF and the output single mode patch code, as shown in Figure 6.16 and Figure 6.17.

Figure 6.16 Oscilloscope trace of the back scattering of the amplifier; pump power is 3 W.

Figure 6.17 The optical spectrum of the back scattering of the amplifier; pump power is 3 W

To test the performance of the laser system, the amplified pulse is launched into 60 m of HNLF. Figure 6.18 shows spectrum of the 387 kHz pulse after the HNLF. Although the HNLF is optimized to the central wavelength of 1550 nm, supercontinuum generation can be observed. Since the zero dispersion wavelength of the fiber is far from 1060 nm, only Raman shift of the pulse can be observed on the

spectrum when pump power is 1.1 W. By increasing the pump power to 3.1 W, the fifth order Raman Stokes appears near the zero dispersion wavelength and generates supercontinuum spectrum with over 300 nm 3 dB bandwidth. This result confirms the high peak power, high pulse energy of the laser system.

Figure 6.18 Supercontinuum generated by the laser system

6.4. CONCLUSIONS

In conclusion, I proposed and demonstrated an all-fiber, all-normal-dispersion, ultra-long cavity Yb-doped passively mode-locked fiber laser. Without any discrete dispersion compensating or normal spectral filtering components, stable mode-locked pulse with sub-MHz repetition rate have been achieved successfully. The nonlinearity induced spectrum broadening of the pulse generates low intensity frequency components that locate at the pulse pedestals as a consequence of the normal dispersion cavity. Due to the saturable absorption property, the SESAM acts as a spectral filter to eliminate the low intensity frequency components back to the cavity.

The compound pulse shaping mechanisms in the extremely large normal dispersion laser cavity stabilize the mode-locking behavior.

By changing the laser cavity length, the master oscillator generated mode-locked pulse with 870 kHz, 387 kHz, 278 kHz and 187 kHz repetition rate, respectively. 6.9 nJ pulse energy was achieved directly from the master oscillator. After amplification, maximum 4.3 μ J wave-breaking free pulse has been achieved when the repetition rate was 187 kHz and the average power was only 0.8 W. Experimental results showed that extending the cavity length not only reduced the repetition rate but also increased the pulse energy. Other than using any costly high-power component, the proposed fiber laser system is able to generate high pulse energy with low average power using a simple and cost-effective all-fiber structure. Compared to fs mode-locked lasers, the laser had much narrower spectrum. The narrow spectrum may be attractive to some applications such as LIDAR system which used Q-switched laser conventionally. The proposed mode-locked laser had the advantages over Q-switched laser in term of all-fiber structure, self-start operation and shorter pulse width at a comparable repetition rate.

7 Conclusions and Recommendations for Future Works

7.1. CONCLUSIONS

This thesis investigated the affect of the saturable absorber and other dissipative components such as spectral filter in the passively mode-locked fiber lasers theoretically and experimentally.

It has been found that the properties of the saturable absorber are particularly important for pulse shaping in a passively mode-locked fiber laser with dispersion managed laser cavity. A numerical model was used to investigate the pulse shaping mechanism. By varying the modulation depth of the saturable absorber, similariton, dispersion managed soliton without sideband, dispersion managed soliton with strong sideband and soliton-like pulse have been achieved respectively in a same laser cavity when the modulation depth are 0.1, 0.4, 0.5 and 0.6 respectively. Experimental result confirmed the simulation result. It has been concluded that higher modulation depth initiated mode-locking with higher pulse peak power and drove the net dispersion of the laser cavity to shift to anomalous range. Therefore, the modulation depth should

be considered as an important parameter to design the dispersion managed soliton laser besides the dispersion map of the laser cavity.

Other than stable mode-locking, noise-like emission has also been achieved in the experiment by adjusting the wave plates which affected the saturable absorption of the NPR. It further emphasized the importance of the saturable absorber in pulse shaping. One interesting result was that the noise-like emission could operate at harmonic mode-locking while previous reports declared that the repetition rate of noise-like pulse should always equal to the fundamental frequency of the laser cavity. The harmonic mode-locking could be controlled by adjusting the orientation of the wave plates or varying the pump power. The noise-like pulses also showed complex pulse interaction dynamics. By correctly setting the wave plates, 28 nJ high energy noise-like pulse was achieved experimentally which could be attractive light source for metrology illumination system.

To further utilize the advantages of NPR mode-locking, a dual-wavelength ultra-short pulse laser was proposed and demonstrated. By inserting PMF into the laser cavity, the NPR components could also act as a comb-like spectral filter. By changing the length of the PMF, the finesse of the comb-like filter can be tuned to 12 nm. Combined with the spectral filtering effect of the gain medium, mode-locking was achieved at 1558 nm and 1570nm simultaneously. The pulse width was 2.4 ps and 2.1 ps respectively. Such dual-wave length laser has potential applications in the WDM optical communication systems. The increasing of wavelength number should be difficult due to the gain competition mechanism.

The effect of saturable absorber has also been investigated in all-normal-dispersion fiber laser. The result showed that the increasing of modulation depth

could be used to avoid multiple-pulsing effect. Multiple-pulsing effect is a widely observed phenomenon which limits the maximum pulse energy. In this thesis, the mechanism of multiple-pulsing in all-normal dispersion was investigated. It was confirmed that spectral filter could act as a pulse energy clamper which induced higher loss to the pulses with higher energy. When the negative feedback of the spectral filter compensated the positive feedback of the saturable absorber, CW light would be amplified in priority and start a new pulse. The pulse number increased while the net loss for the pulses reached a maximum value and the pulse number drop when the net loss for the pulses was minima, and generated strong bistability effect for multiple-pulsing effect.

To optimize the laser design and overcome the multiple pulsing, I demonstrated an analytical analysis on the condition for multiple pulsing. It has been found that the maximum bandwidth and the maximum energy of the pulse were actually decided by the bandwidth of the spectral filter and the modulation depth of the saturable absorber. The pulse energy and the pulse bandwidth could be significantly increased by increasing the modulation depth. This mechanism proposed that the parameters of the saturable absorber could be a factor to optimize the ANDi-laser design.

For laser with long cavity and large net normal dispersion, the wave-breaking effect dominated the pulse energy limitation. Moreover, longer cavity with larger normal dispersion could increase the pulse energy but decrease the pulse bandwidth when the wave-breaking effect became the limitation of pulse energy. Therefore, an optimization on the cavity length could be applied to increase the pulse energy without decreasing the pulse bandwidth.

Based on the theoretical analysis, a passively mode-locked fiber laser with all-normal-dispersion cavity mode-locked by NPR mechanism is demonstrated experimentally. The experiment verified the theoretical analysis and 5.3 nJ pulse with 15 nm bandwidth was achieved at 1560 nm central wavelength.

As the spectral filtering effect is a key factor for pulse dynamics, the dual-peak gain filtering effect of the EDF in a passively mode-locked fiber laser was investigated. The theoretical and experimental results indicated that the dual-peak actually could be treated as two separated gain filters. Incorporating with the filtering effect of NPR, a wavelength switching of mode-locking between 1532 nm and 1560 nm was observed both in the simulation and in the experiment.

At last, pulsing shaping capability of the saturable absorber was investigated by examining a passively mode-locked fiber laser in which the pulse shaping mechanism was only provided by the saturable absorber. An all-fiber, all normal dispersion, ultra-long cavity Yb-doped laser mode-locked by a SESAM was demonstrated experimentally. Due to the saturable absorption property, the SESAM acted as a spectral filter to eliminate the low intensity frequency components and balanced the nonlinearity induced bandwidth broadening and stabilized the mode-locking. Without any discrete dispersion compensating or normal spectral filtering components, stable mode-locked pulse with sub-MHz repetition rate was successfully achieved.

By changing the laser cavity length, the laser generated mode-locked pulse with 870 kHz, 387 kHz, 278 kHz and 187 kHz repetition rate, respectively. 6.9 nJ pulse energy was achieved directly from the master oscillator. After amplification, maximum 4.3 μ J wave-breaking-free pulses have been achieved when the repetition

rate was 187 kHz and the average power was only 0.8 W. Experimental results showed that extending the cavity length not only reduced the repetition rate but also increased the pulse energy. Other than using any costly high-power component, the proposed fiber laser system is able to generate high pulse energy with low average power using a simple and cost-effective all-fiber structure.

7.2. RECOMMENDATIONS FOR FUTURE WORK

- Theoretical work on wave-breaking effect in all-normal-dispersion fiber laser

As discussed in Chapter 5, multiple-pulsing effect is caused by the intra-cavity filtering effect, and the maximum pulse bandwidth can be calculated. However, even when the multiple pulsing effect is avoided, the pulse energy is still under limitation of wave-breaking effect. The pulse breaks down before the spectral limitation is reached. It is already known that the wave-breaking is caused by the large normal dispersion and the strong nonlinearity, but there is no quantitative theory to describe it in passively mode-locked fiber laser. Further theoretical work is needed to find out whether the parameters of the saturable absorber or other parameters can be used to reduce this effect.

- Hybrid mode-locked fiber laser

It has been demonstrated that higher modulation depth could help to suppress the multiple-pulsing effect in the passively mode-locked fiber laser with all-normal-dispersion laser cavity. A cheap and facility method to increase the modulation depth in the laser is to used hybrid mode-locking by incorporating two or more saturable absorption mechanisms, as shown in Figure 7.1.

Figure 7.1 Schematic of a hybrid mode-locked fiber laser

By optimizing the cavity dispersion, high energy ultra-short pulse can be expected due to the suppressing of the multiple-pulsing effect.

- High repetition rate mode-locked fiber laser

It is attractive to achieve mode-locking with a high finesse comb-like filter in the laser cavity. The beating of the multiple wavelengths will generate ultra-short optical pulses with high repetition rate.

A FPF is used to generate multiple wavelengths oscillation, feedback control on both the pump power and the fiber cavity length is used to stabilize the laser. The high repetition rate, low noise ultra-short pulse laser would be attractive for optical fiber communication systems. The challenging part is to optimize the laser cavity to achieve minimum amplitude noise and phase noise, and try to hit the quantum noise limitation.

- Photonics crystal fiber laser

As the pulse energy limitation in the passively mode-locked fiber laser is mainly caused by the fiber nonlinearity, higher pulse energy can be expected by constructing fiber laser based on optical fiber with low nonlinearity.

At present, photonic crystal fiber (PCF) has been developed to a new stage. Many types of high quality PCF is now commercially available. PCF with large mode area (LMA) can have nonlinear coefficient tens of times smaller than the normal silica fiber. LMA-PCF based fiber laser can be employed to boost the energy of the ultra-short optical pulses. Such a laser would be able to generate pulse energy comparable to the conventional solid state lasers.

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