Carbon-nanotube-based devices for passively mode-locked fiber laser applications

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CARBON-NANOTUBE-BASED DEVICES FOR PASSIVELY MODE-LOCKED FIBER LASER APPLICATIONS

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A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy
2014

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.

24/11/2014

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Abstract

Passively mode-locked fiber lasers generating ultrashort pulses have emerged as one of the best light sources in a range of applications including optical communication, frequency metrology, microscopy, and micromachining. One of the key components in passively mode-locked fiber lasers is saturable absorber (SA), which functions to reshape and stabilize intra-cavity pulses through nonlinear absorption. Semiconducting carbon nanotubes (CNTs) have been found to have nonlinear absorption properties in the near-infrared region, and explored extensively as SAs in mode-locked fiber lasers. Such carbon-nanotube-based saturable absorbers (CNT-SAs) could assist mode-locked fiber lasers to produce pulses with excellent performance in both time domain and frequency domain. However, there are still a lot of challenges regarding implementation of CNT-SAs in passively mode-locked fiber lasers such as the relatively low thermal damage threshold of CNT-SAs that limits the intra-cavity power, and the non-optimization modulation depth of CNT-SAs that leads to the unstable pulses in dispersion-managed mode-locked fiber lasers with near-zero net cavity dispersion.

This thesis focuses on the investigation of CNT-based devices and their performance analysis of passively mode-locked fiber laser applications. Different methodologies of CNT deposition to obtain good performance CNT-SAs have been investigated. They include spray-coating, optically-driven deposition, chemical vapor deposition (CVD) of random or aligned CNTs. The main achievements in terms of passively mode-locked fiber laser applications utilizing the fabricated CNT-SAs are summarized as follows.

In order to enhance the thermal damage threshold of CNT-SAs, a novel scheme of fiber-end-type CNT-SA has been proposed. The CNT-layer is optically deposited on fiber connector ends

in a ring pattern for evanescent-field interaction rather than direct interaction. By controlling the inner ring diameter of the deposited CNT-layer, the fiber-end-type CNT-SAs can endure various levels of incident optical power. Experimental results show that the thermal damage threshold of CNT-SA with the inner ring diameter of $\sim 10\text{ }\mu\text{m}$ can be enhanced by $\sim 130\%$ compared to the one without ring pattern. By incorporating the prepared CNT-SAs into an all-fiber Fabry-Perot (FP) laser, the laser can produce pulses with high pulse energy of $\sim 114\text{ nJ}$ in the Q-switching regime, and pulses with short pulse width of $\sim 680\text{ fs}$ as well as high repetition rate of $\sim 211.84\text{ MHz}$ in the mode-locking regime.

The next part focuses on stable pulse generation from dispersion-managed mode-locked fiber lasers with near-zero net cavity dispersion. We figure out that the optimization of modulation depth of SAs is necessary based on the experimental and numerical investigations. Experimental results show that there is an unstable region in the mode-locked fiber lasers with near-zero net cavity dispersion where the lasers only produce random pulse bursts rather than stable pulse trains. Through the implementation of the fabricated high-contrast CNT-SAs in the mode-locked fiber laser, such unstable region can be shrunk by $\sim 31.3\%$ when the modulation depth of CNT-SAs increases from 6.4% to 12.5% . Numerical simulation is found to be consistent with experimental observation. The obtained results are not only applicable to dispersion-managed mode-locked fiber lasers incorporating CNT-SAs, but also provide a general guidance for lasers using similar type of SAs.

The CNT-SA incorporated dispersion-managed fiber laser with near-zero net cavity dispersion has been further applied in fiber-based supercontinuum (SC) generation. Pulse trains with low timing jitter of $\sim 35\text{ fs}$ and pulse width of $\sim 620\text{ fs}$ have been produced from the dispersion-

managed mode-locked fiber laser and launched into a piece of normal-dispersion highly-nonlinear photonic crystal fiber (PCF). The SC output from the PCF covers 223 nm with less than 7-dB power fluctuation showing potential applications in optical communication and frequency metrology.

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Acronyms

Abbreviation

Full Expression

ASE	Amplified Spontaneous Emission
CNT	Carbon Nanotube
CNT-SA	Carbon-nanotube-based Saturable Absorber
CW	Continuous Wave
DCF	Dispersion Compensation Fiber
DMF	Dimethylformamide
DMMLFL	Dispersion-managed Mode-locked Fiber Laser
EDF	Erbium-doped Fiber
EDFA	Erbium-doped Fiber Amplifier
EOM	Electro-Optic Modulator
FBG	Fiber Bragg Grating
FP	Fabry-Perot
FSR	Free Space Range
FWHM	Full-wave at Half Maximum
GLE	Ginzburg-Laudau Equation
GVD	Group Dispersion Velocity
KL	Kerr Lens
LD	Laser Diode
NaCMC	Carboxymethylcellulose
NLSE	Nonlinear Schrödinger Equation
NOLM	Nonlinear Optical Loop Mirror
NPR	Nonlinear Polarization Rotation
OCT	Optical Coherence Tomography
OSA	Optical Spectrum Analyzer
PC	Polarization Controller
PCF	Photonic Crystal Fiber
PDL	Polarization Dependent Loss
PMMA	Polymethylmethacrylate
PVA	Polyvinylacohol
P3HT	Poly 3-hexylthiophene-2.5-diyl
RI	Refractive Index
SC	Supercontinuum
SDS	Sodium Dodecyl Surfate

SESAM	Semiconductor Saturable Absorber Mirror
SHG	Second Harmonic Generation
SMF	Single-mode Fiber
SPM	Self-phase Modulation
SNR	Signal-to-noise Ratio
SSA	Signal Source Analyzer
VACNT	Vertically-aligned Carbon Nanotubes
WDM	Wavelength-division Multiplexing
XPM	Cross-phase Modulation

Chapter 1 Introduction

This chapter addresses motivation and objective of the research project, and lists originality and major contribution of the work accomplished.

1.1 Background and Motivation

Passively mode-locked fiber lasers generating ultrashort pulses with duration ranging from picoseconds (ps) to femtosecond (fs) have emerged as one of the best light sources in a broad range of applications including optical communication, frequency metrology, microscopy, and micromachining [1]. The first report of passively mode-locked laser was done by Gurs and Muller in 1963 [2]. Since then, gas mode-locked lasers and bulk ultra-fast lasers have dominated in both industry and academia for a long time until the advent of the actual fiber lasers in 1990s [3]. With the rapid development of core technologies as relevant to fiber lasers including fiber amplifier, dispersion tailoring, and nonlinearity management, passively mode-locked fiber lasers are considered to be superior to gas and solid-state mode-locked lasers in terms of high beam quality, alignment-free operation, compact and simple system, and good ability of robustness .

To offer the possibility of passive mode-locking of lasers, one of the key elements is saturable absorber (SA), which functions to reshape and stabilize the intra-cavity pulses through nonlinear absorption [4]. In earlier days, the main techniques to achieve the function of a SA were based on optical Kerr lens (KL), nonlinear polarization rotation (NPR), nonlinear optical loop mirrors (NOLM), and semiconductor saturable absorber mirrors (SESAMs). In recent years, semiconducting carbon nanotubes (CNTs) have

been found to have the nonlinear absorption properties in the near-infrared region, and explored extensively as SAs in mode-locked fiber lasers [5]. Historically, the first synthesis of single-walled CNTs was done by S. Iijima in 1993 [6], and this finding promoted the extensive research of the electrical, mechanical, electromechanical and chemical properties of CNTs. In 2002, Y. Chen *et al.* firstly discovered optical switching properties of CNTs at 1.55 μm [7]. The results reveal that CNTs have an exciton decay time less than 1 ps and exhibit an optical induced transparency. Based on these results, the authors predicted that CNTs could be the candidate for ultra-fast all-optical switches. Two years later, S. Y. Set *et al.* firstly demonstrated a passively mode-locked fiber laser incorporating CNTs that produced a pulse train with pulse width of ~ 1.1 ps and spectral bandwidth of 3.7 nm [8]. The results proved the possibility of CNT-SAs in fiber lasers for pulse generation, which could be considered a milestone in this research field. In the following years, CNT-SAs were confirmed to be the strong candidate for SAs in mode-locked fiber lasers to produce optical pulses with excellent performance including broad spectral bandwidth, ultrashort pulse width, high repetition rate, and low timing jitter.

Comparing CNT-SAs with the existing SAs that are based on nonlinearity of intracavity components including KL, NPR, and NOLM, CNT-SAs have remarkable advantages as follows. (i) Predefined modulation depth: once fabricated, the modulation depth of CNT-SAs is fixed that can be experimentally qualified and reproduced. (ii) Environmentally and mechanically stable: CNT-SAs can be independent of the laser cavity, insensitive to the change of environmental temperature and vibration of polarization state. (iii) Small size and compatible to fibers: CNT-film can be easily

integrated with fiber surfaces; moreover, CNT-solution can be filled into fiber micro-slots. Comparing CNT-SAs with the existing SAs using SESAMs, CNT-SAs have the outstanding merits as follows. (i) Fast recovery time: the recovery time of CNTs is less than 1 ps. (ii) Wide operation wavelength: provided that the tube diameter is in a broad range of distribution, CNTs can absorb light from UV to near-infrared. (iii) Work in both transmission mode and reflective mode: CNT-SAs are capable of working in ring-configuration lasers, linear-configuration lasers, and bidirectional lasers. Owing to these advantages, CNT-based devices become strong candidates being SAs for mode-locked fiber lasers to achieve better performance. And that motivates the research project.

However, some challenges still exist in the application of CNT-SAs in mode-locked fiber lasers that need to be solved. (i) The thermal damage threshold of CNT-SAs is an issue: most techniques to improve the thermal damage threshold of CNT-SAs so far are relatively complicated because they rely on either the modification of fiber structures or the incorporation of additional heat-resistant or heat-dissipation materials. (ii) The influence of SAs on stability of dispersion-managed mode-locked fiber lasers has not been investigated systemically yet: there is a dispersion gap in mode-locked fiber lasers with near-zero net cavity dispersion where stable pulse trains cannot be produced, and this dispersion gap is related to the modulation depth of SAs. (iii) For the application of CNT-based mode-locked fiber lasers, there is still a lot of room for innovation, for instance, flat supercontinuum generation and high-power pulse formation.

1.2 Objective

The objective of this research is to solve above problems and improve CNT-based mode-locked fiber lasers with better performance. It covers: (i) designing and fabricating CNT-SAs with good performance including high thermal damage threshold as well as simple structure; (ii) improving the stability of mode-locked fiber lasers by the optimization of CNT-SAs together with a design of laser cavity; (iii) extending the application of CNT-based mode-locked fiber lasers to various fields.

1.3 Major Contributions

The original contributions in this thesis are listed as follows.

(1) Track and validate the method of optically-driven deposition of CNTs onto standard single-mode fibers (SMF) in order to fabricate CNT-based fiber devices, and extend the method to special optical fibers including tapered fibers and side-polished fibers. By controlling over incident power and time duration, CNT-layers in a pattern of ring can be deposited onto the end-face of a standard SMF. The inner ring diameter of CNT-layer shows a dependence on the incident power. By the design of taper diameter, tapered fibers are coated with an evenly-distributed CNT-layer that is better than those in current reports. By the optimization of polished depth, side-polished fibers are coated with a thin CNT-layer by optically-driven deposition method for the first time.

(2) Demonstrate the possibility of the direct growth of vertically-aligned CNTs (VACNTS) on side-polished fibers for device application by using chemical vapor deposition method for the first time. The scanning electron microscopy (SEM) images

and Raman spectrum are characterized confirming that VACNTs are successfully grown on optical fiber.

(3) Propose a novel scheme of fiber-end-type CNT-SAs for enhancing the thermal damage threshold, in which CNTs are deposited on fiber connector ends in a ring pattern for evanescent-field interaction instead of direct interaction. The thermal damage threshold of such a CNT-SA with inner ring diameter of $\sim 10\ \mu\text{m}$ is found to be increased by $\sim 130\%$ compared with an evenly deposited one. An all-fiber Fabry-Perot (FP) configuration laser is further developed to study the CNT-based device performance in laser applications. When the laser is incorporated with the proposed CNT-SAs with ring pattern that operates in Q-switching regime, the output pulse energy is scaled up to $\sim 114\ \text{nJ}$ which is found competitive to similar report utilizing CNT-SAs. When the laser operates in mode-locking regime, the laser can produce pulses with short pulse width of $\sim 680\ \text{fs}$ as well as high repetition rate of $\sim 211.84\ \text{MHz}$. Furthermore, since the developed mode-locked fiber laser can sustain the relatively high intra-cavity power, the formation of bound states of soliton with a high fundamental repetition rate is demonstrated in CNT-based mode-locked fiber laser for the first time.

(4) Figure out that an optimization of modulation depth of CNT-SAs is necessary for dispersion-managed mode-locked fiber lasers because the effect of saturable absorption is one way to balance the spectral filtering from gain fiber, especially for mode-locked fiber lasers with near-zero net cavity dispersion. Experimental results show that the unstable region of mode-locked fiber lasers with near-zero net cavity dispersion can be shrunk by $\sim 31.3\%$ when the modulation depth of CNT-SA is increased from 6.4% to

12.5%. Numerical analysis is performed that further confirms the experimental observation. The optimized results can be a general guidance for the similar dispersion-managed fiber laser systems.

(5) Demonstrate a flat supercontinuum (SC) generation by a 1.55- μm dispersion-managed mode-locked fiber laser incorporating CNT-SAs and a normal dispersion highly nonlinear photonic crystal fiber (PCF) for the first time. The mode-locked fiber laser with a short-cavity length is dispersion-managed which has net cavity dispersion close to zero. Pulse trains generated from the CNT-based dispersion-managed mode-locked laser exhibit high repetition rate of 123 MHz, low timing jitter of 35 fs and narrow pulse width of 620 fs. Such clean femtosecond-pulse trains are launched into a normal dispersion highly nonlinear PCF for spectral broadening. Since pulse trains propagate in the normal dispersion regime of PCF only, a flat SC ranging from 1450 nm to 1650 nm at -20-dB power level is achieved due to linear frequency chirp induced by self-phase modulation. This demonstration puts a step forward for CNT-based mode-locked fiber lasers in practical applications.

1.4 Thesis Organization

The thesis is organized as follows.

Chapter 1 includes motivation, objective and major contribution of research project.

Chapter 2 introduces the background of CNTs and passively mode-locked fiber lasers.

The literature review about CNT-based devices in passively mode-locked fiber lasers is also given.

Chapter 3 presents the theory necessary to model passively mode-locked fiber lasers. The general equations are derived to describe pulse propagation in each component.

Chapter 4 describes fabrication methods of CNT-based devices including mechanical spray, optically-driven deposition and chemical vapor deposition.

Chapter 5 presents an enhancement of thermal damage threshold of CNT-SAs by exploring the scheme of evanescent-field interaction with CNTs. CNTs are deposited on fiber sidewall of a side-polished fiber for CNT-light interaction in a long distance. Moreover, CNTs are deposited on fiber end in a ring pattern for evanescent-field interaction with CNTs in a thin-film format. The laser performance incorporated with the two proposed CNT-based devices are experimentally investigated.

Chapter 6 shows the optimization of modulation depth of CNT-SAs in stabilization of dispersion-managed mode-locked fiber lasers with near-zero net cavity dispersion. The experimental investigation and the numerical analysis are both performed.

Chapter 7 extends the application of dispersion-managed mode-locked fiber lasers incorporated with CNT-SAs to flat supercontinuum generation. The experimental investigation and the numerical analysis are both conducted.

Chapter 8 concludes the research accomplished and suggests the possible future works.

Chapter 2 Literature Review

This chapter introduces the background of CNTs and its applications in passively mode-locked fiber lasers. The technology about CNT-based devices in passively mode-locked fiber laser applications is reviewed.

2.1 Background

2.1.1 Introduction of Carbon Nanotubes (CNTs)

CNTs are mainly classified into multi-walled CNTs and single-walled CNTs. Single-walled CNTs are mostly explored in electronic and photonic applications. Single-walled CNT is allotropy of carbon, which is regarded as rolling up of an atom thick layer of carbon with a cylindrical nanostructure. It has a typical diameter of ~ 1 nm and a length scale of ~ 1 μm , therefore single-walled CNT is considered to be an ideal one-dimensional material in the world. Depending on the rolling angle and diameter, single-walled CNTs behave in a way like either semiconductors or metals [9]. Semiconducting CNTs have direct energy band-gaps that can absorb light from UV to near-infrared with unique optical properties [10]. In particular, third-order nonlinearity property of CNTs is of great interest, which promises significant value in academic research as well as engineering applications. This section starts with an introduction of the band structure and the optical absorption of CNTs, and then presents the nonlinear optical properties of CNTs and its laser applications. Unless noted otherwise, the abbreviation of CNT in the thesis refers to single-walled CNT.

2.1.1.1 Band Structure and Optical Absorption

The structure of a CNT is determined by how it is rolled from an atom graphene layer.

A useful parameter, named chiral vector $\vec{C}_h$, is introduced to identify any structure of CNT:

$$\vec{C}_h = m\vec{a}_1 + n\vec{a}_2 \equiv (m, n) \quad (2-1)$$

Where m and n are integers, $\vec{a}_1$ and $\vec{a}_2$ are the unit vectors of hexagonal honeycomb lattice in an atom graphene layer, as shown schematically in Fig. 2-1. Suppose that CNT is cut along line $\vec{OB}$, which is parallel to the longitudinal axis of tube, the unfolding CNT could be treated as an atom graphene layer with a fixed width and a semi-infinite length. The direction of $\vec{C}_h$ is perpendicular to $\vec{OB}$, while the length of $\vec{C}_h$ denotes the perimeter of CNT.

Figure 2-1 Illustration of single-walled carbon nanotube (CNT) structure by folding the graphene layer.

Once the chiral vector $\vec{C}_h$ is given the diameter (d) and the rolling angle (θ) of CNT can be derived by:

$$d = \frac{|\vec{C}_h|}{\pi} = \frac{\sqrt{3}a_{c-c}}{\pi} \sqrt{m^2 + mn + n^2} \quad (2-2)$$

$$\theta = \tan^{-1} \frac{\sqrt{3}n}{2m+n} \quad (2-3)$$

where $a_{c-c} = 1.42\text{\AA}$ is the carbon-carbon bond distance.

The reason why the chiral vector $\vec{C}_h$ is of great importance to CNT is that $\vec{C}_h$ indicates whether the cutting line $\overline{OB}$ crosses over a “Dirac point” or not. The “Dirac point” is at where valence band and conduction band touch, which is frequently used to describe a two-dimensional graphene [5]. If the cutting line $\overline{OB}$ crosses over a “Dirac point”, CNT behaves in a way like a metal. Otherwise, CNT is compared to a semiconductor. The criterion for identifying semiconducting CNT can be given by:

$$m - n \neq 3k \quad (2-4)$$

in which k is an integer. For example, CNT showing a chirality of (10, 0) is semiconducting, while CNT showing a chirality of (9, 0) is metallic.

Differing from a two-dimensional graphene, CNT has to take into account the additional quantization arising from the electron confinement around CNT circumference [5]. Instead of the continuous energy level in conduction and valence band, the band structure of semiconducting CNT exhibits relatively discrete energy levels as shown in Fig. 2-2. The sharp peaks at energy levels of c_1 , c_2 , v_1 and v_2 are named as Van Hove singularities, which are originated mainly from the cuts in an atom

thick layer of carbon. As various chirality implies different cuts, the chirality determines the band structure of CNTs. Optical transitions in CNTs can occur between two band-gaps $c_1 - v_1$ and $c_2 - v_2$, labeled as the first band-gap energy E_{11} and the second band-gap energy E_{22} , respectively. As crossover transitions ($c_x - v_y$, $x \neq y$) are dipole-forbidden and thereby are extremely weak, in general, the first band-gap E_{11} is a dominant channel in optical absorption and thereby determines the optical absorption wavelength.

Figure 2-2 Band structure and density of states for (a) metal CNT and (b) semiconducting CNT (reprint from [5]).

Since chirality is also related to tube diameter, one can find easily the relationship between band-gap energy and tube diameter. Fig. 2-3 shows that the tube diameter is inversely proportional to the first band-gap energy and the resultant absorption wavelength. In other words, one can control the absorption wavelength of CNTs through the distribution of tube diameter. For the optical absorption ranging from 1 μm to 2 μm , the tube diameter should fall in the range of 0.7-1.4 nm.

Figure 2-3 Energy gap of CNTs against tube diameter (reprint from [8]).

2.1.1.2 Nonlinear Optical Properties of CNTs

The key nonlinear optical properties of CNTs are saturable absorption and high third-order nonlinearity.

In nonlinear optics, the optical response of any material to light with intense electromagnetic field can be expressed by polarization $P(t)$ as a sum of power series with the light field strength $E(t)$:

$$P(t) = \epsilon_0 \left\{ \chi^{(1)} \cdot E(t) + \chi^{(2)} \cdot E^2(t) + \chi^{(3)} \cdot E^3(t) + \dots \right\} \quad (2-5)$$

The proportionality of $\chi^{(1)}$ is known as the linear susceptibility and ϵ_0 is the permittivity of free space. The quantity $\chi^{(2)}$ is second order nonlinear optical susceptibility that is responsible for second harmonic generation (SHG). It is believed $\chi^{(2)}$ is large in some CNTs but the relevant studies are not active. $\chi^{(3)}$ is known as third order nonlinear optical susceptibility that is responsible for saturable absorption and

optical Kerr effect. $\chi^{(3)}$ is a complex quantity $\chi^{(3)} = \text{Re}(\chi^{(3)}) + i\text{Im}(\chi^{(3)})$. The imaginary part corresponds to nonlinear absorption and the real part is responsible for nonlinear refractive index.

In semiconducting CNTs, a variation of incident light intensity results in a change of optical absorption and refractive index. The optical absorption coefficient α and the refractive index n related to the light intensity I are given by expressions [11]:

$$\alpha(I) = \frac{\alpha_0}{1 + I/I_s} \approx \alpha_0 + \beta I = \alpha_0 + \frac{3\omega \text{Im}(\chi^{(3)})}{2\varepsilon_0 c^2 n_0^2} I \quad (2-6)$$

$$n(I) = n_0 + n_2 I = n_0 + \frac{3\text{Re}(\chi^{(3)})}{4\varepsilon_0 c n_0^2} I \quad (2-7)$$

where β and n_2 are the nonlinear absorption coefficient and the nonlinear refractive index, respectively. α_0 is the low intensity absorption coefficient, I_s is the saturation intensity, ω refers to the frequency of incident light, n_0 is to the refractive index, ε_0 is the vacuum permittivity, and c refers to the speed of light in vacuum. β and n_2 are experimentally measured as high as $(5.4 \pm 2.0) \times 10^{-7} \text{ cm/W}$ and $(1.1 \pm 0.5) \times 10^{-11} \text{ cm}^2/\text{W}$, respectively [11]. The measured β value of CNTs is about two orders of magnitude greater than CaF_2 and BaF_2 crystals, which are used as optical windows and achromatic lenses. The measured n_2 value of CNTs is almost nine orders of magnitudes higher than silica, which is exploited as traditional transmission medium in telecommunication.

Figure 2-4 Schematic diagrams of (a) photon absorption; (b) saturate absorption; and (c) the typical transmission of CNT-SA.

The saturation absorption property of CNTs is originated from its intensity-dependent absorption effect whose formula is given in Eq. (2-6). When the intensity (I) of input beam is above certain level ($I_1 \gg I_{sa}$), the optical absorption by CNTs is not equal to but relatively smaller than the absorption when input intensity is low ($I_2 \ll I_{sa}$), i.e. $\alpha(I_1)_{I_1 \gg I_{sa}} < \alpha(I_2)_{I_2 \ll I_{sa}}$. Such decrease in optical absorption is regarded as saturable absorption. The physical mechanism of such saturable absorption in semiconducting CNTs is schematically shown in Figs. 2-4(a)-(b). At sufficiently high incident light intensity, atoms in the ground state of CNTs (open circles) are excited into an upper energy state (solid circles) at a rate that there is insufficient time for them to recover back to the ground state before the ground state becomes depleted, and subsequently the absorption saturates. The time for semiconducting CNTs to recover from their first excitonic state to the ground state is mainly determined by nonradiative decay [12]. Fig.

2-4(c) shows the typical transmission of CNT-SA exposed to incident light at various input intensity: light with high intensity undergoes less absorption while light with low intensity suffers more loss. In the figure, the difference between the minimum and the maximum in the optical transmission is measured to be $\sim 12\%$. Such discrimination in the optical transmission is termed as modulation depth which is desirable for pulse reshaping in passively mode-locked fiber lasers.

Figure 2-5 The time evolution of transmitted probe beam of $1.55\ \mu\text{m}$ (reprint from [7]).

The recovery time of CNTs plays an important role in laser applications as it determines whether the CNTs will distort pulse shape. The recovery time refers to the exponential time constant of absorption recovery after a saturating pulse. Fig. 2-5 shows an example of a pump-probe measurement to determine the recovery time of CNTs [7]. The pump and the probe have pulse duration of 150 fs and wavelengths of $0.78\ \mu\text{m}$, $1.55\ \mu\text{m}$, respectively. After the pulses propagate through CNTs, the tailing edge of the pulse is slightly delayed which leads to an asymmetrical shape of the pulse. It is due to the tailing edge of pulse having little absorption and relatively high transmission within the

recovery time as the CNTs saturated by the leading edge. The results point out that semiconducting CNTs excited to their excitonic state exhibit a very fast recovery to ground state with a time constant less than 800 fs, which is faster than traditional semiconductor saturable absorber mirrors with recovery time in a range from a few to hundreds of picoseconds.

2.1.2 Introduction of Passively Mode-Locked Fiber Lasers

Various fiber lasers are developed to meet requirements of different applications in terms of optical power, wavelength and *etc.* According to the laser output, there are two types of fiber lasers: continuous wave (CW) lasers and pulsed lasers as shown in Fig. 2-6. CW lasers output continuous wave with a constant power in time domain and emit almost a mono-frequency light with narrow line-width. On the contrary, pulsed lasers produce optical pulses periodically and show a wide spectral bandwidth. Due to high peak power, pulsed lasers can be widely used in nonlinear optics, laser surgery, and manufactory. Two mechanisms are involved to generate optical pulses: mode-locking and Q-switching. Especially, fiber lasers based on mode-locking mechanism can produce pulses with excellent performance in terms of pulse width, repetition rate, spectral bandwidth, peak power. This section introduces to the definition of mode-locking and then to the saturable absorbers incorporated in passively mode-locked fiber lasers.

Figure 2-6 Classification of fiber lasers: continuous wave (CW).

2.1.2.1 Fundamentals of Mode-Locking

To begin with, the definition of “mode-locking” is given. Here modes refer to cavity longitudinal modes. Since two mirrors confine light within a laser oscillator, only the resonance frequencies exist as shown in Fig. 2-7. These discrete resonance frequencies can emit when cavity gain is larger than cavity loss. The separation between two adjacent modes is determined by the distance of mirrors. Provided that L refers to cavity length, and c is speed of light in vacuum, the frequency separation is given by:

$$\Delta f = \frac{c}{2L} \quad (2-8)$$

For single longitudinal mode lasing, the optical field is expressed as

$$E(t) = E_0 e^{j(2\pi f_0 t + \phi_0)} \quad (2-9)$$

Figure 2-7 Schematic diagram of longitudinal modes in fiber lasers.

For the multi-mode lasing, it is modified as:

$$E(t) = \sum_{m=-N}^{m=N} E_m e^{j(2\pi f_m t + \phi_m)} \quad (2-10)$$

where $f_m = f_0 + m\Delta f$ (f_0 is carrier frequency, m is an integer), ϕ_m is the corresponding phase item. Suppose that phases of modes are all locked together and all the modes have the equal amplitude:

$$\phi_m = \phi_{m-1} = 0 \quad (2-11)$$

$$E_m = E_0 \quad (2-12)$$

Under above two conditions, the total intensity of multi-modes laser is expressed as:

$$|E(t)|^2 = E_0^2 \frac{\sin^2[(2N+1)\pi\Delta f t]}{\sin^2(\pi\Delta f t)} \quad (2-13)$$

From the Eq. (2-13), one can find that the output of laser can be regarded as a carrier wave of frequency f_0 amplitude-modulated by the function $|E(t)|$. Fig. 2-8 shows intensity $|E(t)|^2$ versus the number of cavity modes. As the number of mode increases, pulse width is greatly narrowed down. Therefore, mode-locked lasers are capable to produce optical pulses with ultrashort pulse width.

Figure 2-8 Pulse width shortening against the number of longitudinal modes.

In practice, in order to construct a laser oscillator, three basic components are necessary: gain medium, pump, and cavity feedback as shown in Fig. 2-9. The gain medium absorbs light from the pump source and converts it to the emission wavelength through the stimulated emission of electrons from a higher energy state to a low energy state. The cavity feedback is included to form the closed-loop resonator, which can be provided by mirrors. The laser only produces continuous wave in this case.

Figure 2-9 Typical configuration of a mode-locked fiber laser.

To achieve pulse generation based on mode-locking mechanism, an additional component is required: loss modulator. By periodically adjusting the cavity loss with time through loss modulator, continuous wave tends to break up into a sequence of optical pulse train. The loss modulator can be an active device, for instance, electro-optic modulator (EOM), thereby the laser is labeled as actively mode-locked fiber laser. On the contrary, the loss modulator can be passive device, such as saturable absorber (SA), so the laser is termed as passively mode-locked laser. In recent years, passively mode-locked fiber lasers have emerged as one of the best optical pulsed sources due to their relatively simplicity and ability to generate transform-limited optical pulses in the picosecond and sub-picosecond regimes.

2.1.2.2 Saturable Absorbers (SAs) for Mode-Locking

Figure 2-10 Schematic diagrams of (a) nonlinear transmission of SA and (b) pulse reshaping.

A saturable absorber can function as a loss modulator, which is significant to the pulse formation in passively mode-locked fiber lasers. Figs. 2-10(a) and (b) schematically show how a SA interacts with an incident pulse. Due to intensity-dependent absorption of a SA, the different parts of an optical pulse will undergo various optical absorptions when the pulse is passing through a SA. The leading and trailing edges of pulse with relatively low intensity are cleared up by strong absorption, while the center part with

high intensity passes through the SA with weak attenuation. As a result, the signal-to-noise ratio (SNR) of an optical pulse can be enhanced. Such a pulse-resaping function is vital in the initial phase of pulse formation. Once the pulse is gradually built up at a certain power level after several cavity round-trips, a soliton-like pulse can be formed from the fiber laser through the dynamic balance between anomalous dispersion and optical Kerr effect.

Four parameters are generally used to evaluate the performance of a SA: recovery time, non-saturation loss, saturation intensity, and modulation depth as shown in Fig. 2-10(a). As it is introduced, the recovery time corresponds to the decay time of the excitation after an exciting pulse. If the recovery time of SA is larger than pulse duration, the SA is labeled as a slow SA. On the contrary, it is a fast SA. The non-saturation loss denotes the intrinsic absorption of a SA at the unbleached value, which needs to be minimized in most of applications. The saturation intensity refers to the optical intensity where the absorption is reduced at the half of its unbleached value. It is related to the power threshold for the laser to achieve mode locking. Among all performance indexes, the key parameter of SA is modulation depth that refers to the difference between the maximum and minimum in optical absorption. Such modulation depth determines the capability of SA for pulse reshaping.

Two types of SAs are currently explored in passively mode-locked fiber lasers. The first type of SAs is not a concrete SA but an artificial one (also named “effective” SA), which is based on exploring fiber nonlinearity including NPR and NOLM. Such kind of artificial SA is completely dependent on the nonlinear effect of the acting fiber in which the modulation depth can be adjusted by the setting of cavity components. The second

type of SAs is semiconductor SAs including SESAMs, CNTs, and graphene. The semiconductor SAs are independent of cavity settings, which offer the advantage of environmental robustness in practical applications. Among the above SAs, CNT-SAs have shown great potential for passively mode-locked fiber laser applications. In the next section, a brief review of CNT-based mode-locked fiber lasers is given.

2.2 State of the Art

Figure 2-11 The number of publications on the subject of CNT-based fiber lasers.

Fig. 2-11 shows the number of papers published in journals as well as conferences about the CNT-based fiber lasers by searching in a database (*Scopus*). It clearly shows a growing trend of interest in the research subject of CNT-based fiber lasers. The subject has been studied in many groups worldwide in recent ten years. The major research institutes are University of Tokyo, University of Cambridge, Russian Academy of Sciences, Nanyang Technological University, National Institute of Advanced Industrial

Science and Technology in Japan, University of Arizona, Hong Kong Polytechnic University, and Imperial College London. Recently, several companies have provided the commercial products of CNT-based mode-locked fiber lasers including *Kphotonics* and *Alnair Labs*.

Figure 2-12 Research interests on the subject of CNT-based fiber lasers.

By looking into keywords of the published papers, the research interests in CNT-based fiber lasers can be summarized as shown in Fig. 2-12. A part of research interests goes to the fabrication and characterization of CNT-SAs. The majority of research interests focus on advancing the mode-locked fiber lasers incorporating CNT-SAs to achieve excellent laser performance. In addition, a portion of research projects touches on the application of CNT-based mode-locked fiber lasers, which shows the potential usefulness of the lasers in various fields.

2.2.1 Fabrication and Characterization of CNT-SAs

CNTs are nanostructure materials, and required to be integrated with a particular kind of host as a device. In order to obtain CNT-SAs that are compatible with all fiber system, the chosen of a host becomes crucial. The initial idea to construct CNT-SAs is sandwiching a layer of purified CNTs between two quartz substrates [8, 13-15]. In order to incorporate the substrates into a fiber system, additional optical lens to couple light are required. However, the free-space coupling leads to an increase of insertion loss and a reduction in mechanical robust of CNT-based devices.

Table 2-1 Summary of the Selected Polymer for CNT-SAs

	Solvent	Polymer
Aqueous solvent	SDS/water	PVA
	SDBS/water	PVA
	NaCMC/water	NaCMC
Non-aqueous solvent	DMF	PC
	THF	PMMA or PS
	DCB	P3HT, SMMA, PC

Sodium Dodecyl Sulfate (SDS); Sodium Dodecyl Benzene Sulfonate (SDBS); Sodium Carboxymethyl Cellulose (NaCMC); Dimethylformamide (DMF); Tetrahydrofuran (THF) ; Dichlorobenzene (DCB); Polyvinylalcohol (PVA); Polycarbonate (PC); Polymethylmethacrylate (PMMA); Poly 3-hexylthiophene-2,5-diyl (P3HT); Polystyrene (PS); Styrene Methyl Methacrylate (SMMA).

In order to overcome these limitations, CNT-polymer composites have been widely proposed as polymer composites can be conveniently sandwiched between two fiber-ferrules. There are three criteria for choosing the suitable polymer [16]: (i) high transparency at the operation wavelength; (ii) well matching the CNT-solvent and good dispersion of CNT particles; and (iii) smooth surface of CNT-polymer composite. The current usage of polymers for CNT-SAs is summarized as shown in Table 2-1. In the

case of CNT dispersion in aqueous solvent, the water-soluble polymers are necessary, for instance, polyvinylalcohol (PVA) [17-20], and sodium carboxymethyl cellulose (NaCMC) [21-24]. Such kinds of CNT-polymer composites are typically showing smooth surface. In the case of CNT dispersion in non-aqueous solvent, the polymers including polycarbonate (PC) are good candidates due to their better transparence and environmental stability [25, 26].

An alternative solution to fabricate CNT-SAs without additional optical lens as well as extra polymers is to utilize optical fibers as the original host. In particular, optically-driven deposition method to deposit CNTs on fiber surface is of great interest due to its controllability. For optically-driven deposition method, fibers guide light beam into a CNT-solvent, where the movement of CNTs particles towards fibers could take place when the injection light is at certain power levels. Optical tweezer effects and thermophoresis are the origin of such movement [27, 28]. The merits of optically-driven deposition method are the relatively controllable process and the efficient usage of CNTs. In addition, the formation of CNTs on fiber ends could be manipulated either in ring pattern [29] or sphere [30] for the functional CNT-based devices.

One major issue of the existing CNT-SAs is the relatively low thermal damage threshold in practical application. Although the individual CNT is predicted to have high thermal conductivity, the aggregations of CNT particles could weaken the transfer of heat. As a result, the heat dissipation is not fast leading to significant temperature increase and damaging of CNTs. Indeed, it has been reported that the thermal damage thresholds of CNT-polymer composites are typically less than 30 mW [31]. The

microscopic images of a CNT-film before and after light-induced thermal damage are shown in Figs. 2-13(a) and (b), respectively [31].

Figure 2-13 Microscopic images of a CNT-film (a) before and (b) after light-induced thermal damage (reprint from [31]).

In order to enhance the thermal damage threshold of CNT-SAs, various methods are proposed which can be classified into two categories: (i) slow down the heat accumulation by reducing the optical absorption; and (ii) speed up the heat dissipation by incorporating extra materials. The ideas of reducing heat accumulation are to employ the evanescent-field interaction between the propagating light and CNTs. Since the majority of optical power interacts with CNTs indirectly, CNTs can sustain relatively high power. To achieve an evanescent-field interaction with CNTs, special fibers are required such as side-polished fibers [32-35], tapered fiber [36-39], and micro-slot fibers [40, 41]. By using the scheme of evanescent-field interaction, the thermal damage threshold of CNT-based devices can be enhanced significantly. In order to speed up the heat dissipation, special materials are required, for instance, alumina [42], siloxane [43] and nitrogen [44]. However, above methods are relatively complicated because it is

based on either the modification of fiber structures or the incorporation of extra materials. Therefore, a new scheme in a simpler way to enhance thermal damage threshold of CNT-based devices is much expected.

2.2.2 Development of CNT-based Mode-locked Fiber Lasers

Figure 2-14 Key performance index of mode-locked fiber lasers.

Since the first report in 2003, passively mode-locked fiber lasers incorporating CNT-SAs have shown a rapid development. The key performance indexes of CNT-based mode-locked fiber lasers are illustrated in Fig. 2-14: λ_0 is the center wavelength, $\Delta\lambda$ is the spectral bandwidth, T_0 is the pulse width, f_{rep} is the fundamental repetition rate of pulse train; and $|E_b|^2$ is the peak power. The major achievements of CNT-based mode-locked fiber lasers in terms of performance indexes are reviewed as follows.

CNT-based mode-locked fiber lasers can operate in various center wavelengths covering 1 μm [45], 1.3 μm [14], 1.55 μm [46], and 1.9 μm [22] by employing the gain mediums of ytterbium-doped fiber, erbium-doped fiber, praseodymium-doped fiber, and

thulium-doped fiber, respectively. The schematic diagram is shown in Fig. 2-15. By inserting a suitable tunable filter inside the laser cavity, the center wavelength of spectrum is able to be tuned continuously within the gain bandwidth [47]. In addition to a single-color emission, previous report has shown that two pulse trains from 1.55- μm mode-locked fiber laser and 1- μm mode-locked fiber laser can be passively synchronized to achieve two-color pulsed laser by sharing a common CNT-SA [48].

Figure 2-15 Schematic diagram of mode-locked fiber lasers operating at various center wavelengths by incorporating different gain fibers.

Mode-locked fiber lasers with a large spectral bandwidth could be built by managing the net cavity dispersion to zero [49]. Fibers with opposite group velocity dispersion (β_2) are connected together which lead to temporally stretching and compressing of the pulse in one cavity round trip as shown in Fig. 2-16. Such pulse breathing dynamics reduces the peak phase shift of the pulse per round trip and the instabilities due to the excessive nonlinearity can be deferred to a higher intensity and shorter pulse. Currently, the largest

spectral bandwidth of CNT-based mode-locked fiber lasers operating at 1.55 μm is experimentally demonstrated to be around ~ 63 nm when the net cavity dispersion of laser is ~ -0.003 ps² [50]. The corresponding pulse shows the a transformed-limited pulse width of ~ 74 fs which is far narrower than pulses from the lasers without the management of net cavity dispersion [8]. On the contrary, mode-locked fiber lasers with narrow spectral bandwidth, which generate pulses with ultralong pulse width, could be built by incorporating a narrowband filter. The generation of pulses with pulse width of 1.15 ns and spectral bandwidth of 0.059 nm have been demonstrated from CNT-based mode-locked fiber laser operating at 1 μm [51].

Figure 2-16 Schematic diagram of mode-locked fiber lasers producing pulse trains with ultrashort pulse width by managing net cavity dispersion.

The fundamental repetition rate of pulse train in passively mode-locked fiber lasers is inversely proportional to the cavity round-trip time and therefore it is mainly determined by the cavity length. In order to achieve high fundamental repetition rate, a short cavity length (L) is essential as shown schematically in Fig. 2-17. Nowadays, the highest fundamental repetition rate of pulse trains attained from CNT-based 1.55- μm mode-locked fiber lasers is ~ 19.45 GHz with a total cavity length of ~ 5 mm [52]. Another method of increasing repetition rate of pulse trains from mode-locked fiber lasers is to

operate in the regime of harmonic mode-locking. Multiple pulses with equal time spacing are generated within one cavity round-trip time. The notable results of harmonic mode-locking to increase repetition rate is about ~ 4.9 GHz at 128th-order cavity fundamental frequency [53]. On the contrary, the low fundamental repetition rate of pulse train requires the laser to lengthen the cavity length. The lowest repetition rate of pulse trains from CNT-based 1.55- μm mode-locked fiber laser is ~ 58 kHz with the cavity length of ~ 3.5 km [54].

Figure 2-17 Schematic diagram of mode-locked fiber lasers producing pulse trains with high repetition rate by shortening cavity length.

The single-pulse energy is limited in the conventional soliton fiber lasers which can be explained by soliton theorem theory [55]. When pump power exceeds certain power level, the nonlinear phase shift of pulse is overdriven while cannot be balanced by dispersive phase shift. As a result, the pulse breaks into multiple pulses which lead to the relatively low single-pulse energy. CNT-based 1.55- μm mode-locked fiber lasers operating in conventional soliton regime typically produce pulses with pulse energy less than ~ 100 pJ [55]. In order to increase pulse energy, dispersion-managed fiber lasers generating stretched-pulses are proposed [49]. Previous report has demonstrated that the CNT-based dispersion-managed 1.55 μm mode-locked fiber laser can generate pulses

with pulse energy of ~ 1.4 nJ at net cavity dispersion of ~ -0.013 ps² [43]. In order to further scale up pulse energy, mode-locked fiber lasers with net normal dispersion fibers producing dissipative solitons are attractive. Until now, CNT-based mode-locked fiber lasers operating in dissipative-soliton regime can generate pulses with pulse energy of 8.1 nJ at net cavity dispersion of $\sim +0.18$ ps² [56].

CNT-based mode-locked fiber lasers can produce stable pulse trains with very low noise. In 2010, C. Ouyang *et al.* demonstrated that the stable pulse trains with timing jitter as low as 29.1 fs can be generated from the 1.55- μ m mode-locked fiber laser incorporating CNT-SAs [23]. Such small deviation of temporal pulse positions is very important in many applications including optical communications and optical sampling measurements. In 2011, C. S. Jun *et al.* presented a low-noise harmonic mode-locked fiber laser incorporating CNT-SAs in which the laser exhibited >50 dB side-mode suppression at repetition rate of 943 MHz [34]. In the same year, T. Wu *et al.* reported a low noise fs frequency comb with the free-running line-width of the carrier-envelope offset frequency of ~ 20 kHz by using CNT-coated tapered fiber as the SA in the mode-locked fiber laser system [39].

In addition to the above engineering achievements, investigation on the physical mechanism of CNT-based mode-locked fiber lasers is also an active research direction. In 2008, N. Nishizawa *et al.* demonstrated the generation of a scalar soliton from CNT-based all-polarization-maintaining mode-locked fiber laser [57]. On the other hand, in 2010, J. H. Wong *et al.* reported that vector solitons could be produced from fiber lasers mode-locked by CNTs [58]. In addition to the polarization properties, the pulse-to-pulse

interaction is of great interest. In 2011, X. Wu *et al.* experimentally demonstrated the soliton-molecule (or bound-state solitons) from the passively mode-locked fiber laser incorporating CNT-SAs [59]. Two years later, L. Gui *et al.* systemically studied the phase relationship between the bound states of soliton generated from CNT-based mode-locked fiber lasers [60]. Recently, bound states of vector soliton are found to have characteristics of locked and precessing polarization states [61].

Table 2-2 State of the Art of CNT-based Mode-locked Fiber Lasers

Geometry	Linear ^[46] or ring configuration ^[37]
Center Wavelength	1 μm ^[45] , 1.3 μm ^[14] , 1.55 μm ^[46] and 1.9 μm ^[22]
Spectral Bandwidth	~ 63 nm ^[50]
Pulse Width	Ultrashort pulse of ~ 74 fs ^[50] Ultralong pulse of ~ 1.15 ns ^[51]
Repetition Rate	~ 19.45 GHz ^[52]
Pulse Energy	8.1 nJ ^[56]
Noise	29.1 fs ^[23]
Damage Threshold of thin-film CNT-SA	~ 120 mW ^[62]

Table 2-2 summarizes the state-of-the-art CNT-based mode-locked fiber lasers in terms of key performance indexes. Related to those indexes, we have made certain original contributions where our works can position among the current achievements. They include enhancing the thermal damage threshold of CNT-SAs to 126 mW, raising up pulse energy to 112 nJ, and enhancing laser stability at near-zero net cavity dispersion. Moreover, we have observed bound-states of soliton with high fundamental repetition rate and multiple types of pulses generated from CNT-based mode-locked fiber lasers which have very few previous reports.

2.2.3 Application of CNT-based Mode-locked Fiber Lasers

CNT-based mode-locked fiber lasers have shown a broad range of applications including supercontinuum generation, optical sampling, pump-probe measurement, medicine, and optical sensing.

CNT-based mode-locked fiber lasers generating ultrashort pulses can be selected as pulsed sources for supercontinuum (SC) generation. The related achievements about SC generation include the broad spectral bandwidth of ~ 500 nm and the ultrashort pulse width of ~ 14 fs [63], the high repetition rate of 10 GHz [52], the high power of >5 W [52, 64], and the low noise with free running offset frequency line-width of ~ 20 kHz [39]. Such SC light sources show a great potential for numerous applications, for instance, spectroscopy, pulse compression, and dense wavelength division multiplexing (WDM) applications.

CNT-based mode-locked fiber lasers are very attractive for optical sampling applications due to the ability to generate pulses with very low noise. In 2008, S. Set *et al.* presented the CNT-based $1.55\text{-}\mu\text{m}$ mode-locked fiber lasers as the light source in non-synchronous optical sampling systems, in which the laser generates pulse trains with tunable repetition rate [65]. The results demonstrate the reconstruction of 160 Gbit/s return-to-zero signals without the limitations such as the time-direction ambiguity and the frequency-hole.

CNT-based mode-locked fiber lasers can emit dual-wavelength pulse trains, which is very useful for pump-probe spectroscopy. The emitting pulse trains at each wavelength are slightly walking off with a delay time in the range of femtosecond to picoseconds,

which is desirable for an asynchronous optical sampling. In 2012, X. Zhao *et al.* reported the dual-wavelength CNT-based mode-locked fiber laser being the light sources for pump probe measurement, in which one center wavelength is located at ~ 1532.4 nm and the other one is 1556 nm [66]. Such laser shows the ability for long scanning range at a scanning rate of ~ 466 Hz with a picosecond resolution.

CNT-based mode-locked fiber lasers have shown remarkable advances in the applications of medicine, for instance, eye surgery and optical coherence tomography (OCT). In 2012, S. K. Vartapetov *et al.* reported the application of CNT-based 1- μm mode-locked fiber lasers for ophthalmology laser surgery [67]. The laser generates pulses with repetition rate of 16.7 MHz, pulse energy of 10 nJ, and pulse width of 200 fs after compression, in which a CNT-SA is constructed by coating the CNT-CMC polymers on side-polished fiber. Such a femtosecond fiber laser shows great advantages in eye surgery including the high quality of laser cutting and the environmental robustness. Besides the laser surgery, CNT-based mode-locked fiber lasers can be used in OCT. OCT is one of modern techniques to image a micro-scale cross-section of biological tissue and material. In 2013, S. Ishida *et al.* demonstrated the application of a supercontinuum light source centered at 1.7 μm with an optical power of 43.3 mW in OCT [68]. The seeded pulse for the supercontinuum is generated from a CNT-based 1.55 μm mode-locked fiber laser with pulse width of 605 fs and repetition rate of 109 MHz. By using this supercontinuum light source, a 105-dB sensitivity and an ultrahigh resolution of 4.3 μm are achieved, which shows a great improvement in image contrast and penetration depth.

In addition to above applications, CNT-based bidirectional mode-locked fiber lasers have a potential application in optical sensing, for instance, the precision rotation measurements. In 2008, K. Kieu *et al.* demonstrated bidirectional mode-locked fiber ring lasers incorporating CNT-coated tapered fiber as a SA for the application of gyroscopes [69]. The beating frequency of the two pulse trains generated from the clockwise and the counterclockwise directions is about 2 MHz with a bandwidth of ~2 kHz. Such a CNT-based all-fiber bidirectional mode-locked laser in the application of gyroscopes shows the advantages including robust, low cost, and ultralarge sensing ranges.

From the results of literature survey, one can find that CNT-SAs can assist mode-locked fiber lasers to produce pulses with excellent performance including tunable operation wavelength, wide spectral bandwidth, ultrashort pulse width, high repetition rate, high pulse energy, and low time jitter. CNT-based mode-locked fiber lasers have shown a broad range of applications covering the fields of optical communications, optical sensing, medicine, and spectroscopy.

Chapter 3 Theoretical Framework of Passively Mode-locked Fiber Lasers

This chapter includes the theories describing passively mode-locked fiber lasers. The general equations of pulse propagation in each cavity component are derived to form the bases for the following chapters about the experimental studies of pulse formation.

3.1 Introduction

The advent of various optical fibers fuels the development of mode-locked fiber lasers. In order to well understand the working mechanism of mode-locked fiber lasers, it is necessary to understand how the pulse propagates along optical fibers. In general, a mode-locked fiber laser consists of two types of fibers: one is the passive fiber, for instance, standard SMF, HI1060 fiber, dispersion-compensation fiber (DCF); the other is the active fiber that is doped with various rare-earth elements including erbium, ytterbium, and thulium.

The significance of a passive fiber is to support pulse propagation. Two effects are mainly involved when a pulse propagates along the fiber: chromatic dispersion and self-phase modulation. The chromatic dispersion refers to the dependence of phase velocity on optical frequency when pulse interacts with a dielectric medium. Due to various phase delay at different frequency components, a chirp-free pulse consisting of a frequency comb tends to broaden pulse duration after propagation. Self-phase modulation refers to the self-induced phase shift experienced by an optical field with a high intensity. The two effects can be included in nonlinear Schrödinger equation

(NLSE) in order to model pulse propagation along a passive fiber. In the case of an optical pulse propagating along a passive fiber with anomalous dispersion, the dispersion induced phase delay can be cancelled by the phase caused by self-phase modulation. As a result, the pulse behaves as a soliton whose shape is maintained with little change during propagation.

The importance of an active fiber is to achieve pulse amplification. Compared with a passive fiber, the active fiber shares some similar features: it induces the pulse to experience chromatic dispersion and self-phase modulation. On the other hand, since a pulse gets extra energy via a gain fiber under pumping, two additional effects need to be considered: gain saturation and gain filtering. Due to the finite population inversion of the dopant ions in a gain fiber, the gain has a tendency to decrease when the input pulse is at certain of high power level. The gain filtering is originated from a finite gain bandwidth, which limits the spectral broadening through the effect of self-phase modulation. To analyze the pulse propagation in a gain fiber, instead of the nonlinear Schrödinger equation, the complex Ginzburg–Landau Equation (CGLE) is employed.

In addition to optical fibers, saturable absorbers need to be taken into account because it plays important roles in pulse reshaping and stabilization in mode-locked fiber lasers. According to the relative mismatch between recovery time of a SA and pulse duration, SAs can be classified into two types: the fast SA and the slow SA. A slow SA can assist fiber lasers to achieve a self-started mode-locking operation. On the other hand, a fast SA can enable mode-locked fiber laser to generate an ultrashort pulse width.

When all components are combined together to construct a laser resonator, a single equation named Master equation is explored to analyze mode-locked lasers if the

dispersive and nonlinear changes of pulse are continuously distributed. The equation treats the contribution from all components as an average effect. However, in a real laser, different types of elements construct a cavity and show a discrete distribution of the linear and nonlinear changes. Such discrete effects cause a pulse to encounter more loss than the one in the case of continuous distribution. Therefore, instead of an average effect, the pulse dynamic in a localized position should be taken into account.

3.2 Theoretical Model of Pulse Propagation in Optical Fibers

3.2.1 Pulse Propagation in Single-mode Fibers

An optical fiber is typically a cylindrical waveguide that confines optical field within a core region. Fig. 3-1 shows the schematic diagram of the cross section of a step-index fiber as well as its refractive index profile. The refractive index of fiber core is slightly higher than that of fiber cladding ($n_1 > n_2$) to achieve the total internal reflection of light. In order to characterize optical fiber, two parameters are introduced: core-cladding index difference and V parameter that are given by:

$$\Delta = \frac{n_1 - n_2}{n_1} \quad (3-1)$$

$$V = k_0 a (n_1^2 - n_2^2)^{1/2} \quad (3-2)$$

where $k_0 = 2\pi/\lambda$ with λ the wavelength of light and a the core radius. The V parameter determines the number of modes supported by the fiber. If the condition is satisfied $V < 2.405$, only the fundamental mode can propagate along the fiber in a long distance without attenuation, and thereby the fiber is labeled as single-mode fiber (SMF).

The typical parameters of the SMF in telecommunication are: $a = 8.2\mu\text{m}$, $\Delta \approx 0.36\%$ at $1.55\mu\text{m}$.

Figure 3-1 Schematic diagram of the structure of an optical fiber and its refractive index profile.

When an optical pulse propagates along a SMF, based on the slowly varying envelope assumption, the mathematical expression of electrical field can be treated as a separation of variables in the transverse and the longitudinal directions as shown in Fig. 3-2. $F(x, y)$ represents the transverse distribution of propagation modes in a fiber, while $A(z, t)$ refers to the slowly varying pulse envelope in the longitudinal direction. The field can be written as the product of the two items together with the phase variation:

$$E(\mathbf{r}, t) \approx F(x, y)A(z, t)\exp[i(\beta_0 z - \omega_0 t)] \quad (3-3)$$

where β_0 is the wave number at the center frequency of ω_0 . The Fourier transform of pulse envelope represents its optical spectrum that can be derived as:

Figure 3-2 Representation of electrical field of an optical pulse.

$$\tilde{A}(z, \omega - \omega_0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} A(z, t) \exp[i(\omega - \omega_0)t] dt \quad (3-4)$$

Since the transverse mode distribution $F(x, y)$ is almost unchanging with time when the geometrical parameters of fiber are preset, the mathematical expression of the electric field of an optical pulse in frequency-domain can be simplified by:

$$\tilde{E}(\mathbf{r}, \omega - \omega_0) \approx F(x, y) \tilde{A}(z, \omega - \omega_0) \exp(i\beta_0 z) \quad (3-5)$$

Due to the rich frequency components as well as the high intensity, an optical pulse inevitably experiences the chromatic dispersive and nonlinear effects during propagation. As a result, it leads to a change of pulse shape $A(z, t)$ and spectrum $\tilde{A}(z, \omega - \omega_0)$.

3.2.1.1 Fiber Dispersion

The chromatic dispersion refers to the different responses of a dielectric medium to electromagnetic fields at various input frequencies. On the fundamental level, the origin

of chromatic dispersion of a dielectric medium is related to the characteristics resonance frequencies where the medium absorbs the electromagnetic radiation via oscillations of bound electrons [70]. It can be manifested by the unequal refractive indexes of the medium about frequencies:

$$n^2(\omega) = 1 + \sum_{j=1}^m \frac{B_j \omega_j^2}{\omega_j^2 - \omega^2} \quad (3-6)$$

where ω_j is the resonance frequency. B_j is the strength of j^{th} -order resonance. For a given medium, ω_j and B_j are determined. As the speed of light in medium is related to its refractive index that is given by $c/n(\omega)$, different frequency components of light will travel at different speeds, known as chromatic dispersion.

When a short pulse travels in an optical fiber, chromatic dispersion can cause pulse to broaden significantly because a pulse consists of abundant frequency components. Mathematically, fiber dispersion can be expressed by expanding the mode-propagation constant β in Taylor-series at frequency ω_0 where the pulse spectrum is centered:

$$\beta(\omega) = \beta_0 + (\omega - \omega_0)\beta_1 + \frac{1}{2}(\omega - \omega_0)^2\beta_2 + \frac{1}{6}(\omega - \omega_0)^3\beta_3 + \dots \quad (3-7)$$

where

$$\beta_m = \left(\frac{d^m \beta}{d\omega^m} \right)_{\omega=\omega_0} \quad (m=1, 2, \dots) \quad (3-8)$$

The parameter β_1 and β_2 have the derivatives through the relations:

$$\begin{cases} \beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c} \left(n + \omega \frac{dn}{d\omega} \right) \\ \beta_2 = -\frac{\lambda^2}{2\pi c} \frac{d\beta_1}{d\lambda} = \frac{1}{c} \left(2 \frac{dn}{d\omega} + \omega \frac{d^2n}{d\omega^2} \right) \end{cases} \quad (3-9)$$

in which n_g is the group refractive index, v_g is group velocity, and c is the speed of light in vacuum. Physically speaking, the envelope of an optical pulse propagates at the group velocity. Since β_2 is the differential of β_1 to wavelength, it represents dispersion of the group velocity. Therefore, β_2 is termed as the group velocity dispersion (GVD) parameter, which is responsible for pulse broadening.

3.2.1.2 Fiber Nonlinearity

As described in Eq. (2-5), the optical response of any medium exposed to light with intense electromagnetic field tends to become nonlinear. On the fundamental level, the origin of nonlinear response of a dielectric medium is related to the harmonic motion of bound electrons exposed to an electromagnetic field [70]. In optics fibers, due to the symmetric molecule of SiO₂, the second order nonlinear optical susceptibility $\chi^{(2)}$ is negligible. Therefore, the lowest-order nonlinear effects of optical fibers is originated from the third order nonlinear optical susceptibility $\chi^{(3)}$, which is responsible for third-harmonic generation (THG), four-wave mixing (FWM), and nonlinear refractive index. Unless an optical fiber is designed to generate new frequencies by satisfying the phase-matching condition, otherwise, the nonlinear effects of the fiber are particularly weak including THG and FWM. In most cases, the nonlinear effect is dominated by the

change of refractive index under the high intensity of an applied field, which can be simplified by:

$$\tilde{n}(\omega, |E|^2) = n(\omega) + \Delta n(\omega) = n(\omega) + n_2 |E|^2 \quad (3-10)$$

where $n(\omega)$ is the linear part of refractive index given in Eq. (3-6), while $\Delta n(\omega)$ is the nonlinear part of refractive index. $|E|^2$ is the optical intensity of the applied field, n_2 is called the nonlinear-index coefficient which is related to $\chi^{(3)}$ with the relationships of:

$$n_2 = \frac{3}{8n} \text{Re}(\chi^{(3)}) \quad (3-11)$$

in which $\text{Re}(\chi^{(3)})$ accounts for the real part of $\chi^{(3)}$. Such an intensity-dependent refractive index in optical fibers causes a number of interesting nonlinear phenomena. Two nonlinear effects are widely investigated: self-phase modulation (SPM) and cross-phase modulation (XPM). Self-phase modulation refers to the self-induced phase-shift experienced by an optical field during propagation. The phase of an optical field after propagation along fiber is changed by:

$$\phi = \tilde{n}k_0L = (n(\omega) + n_2 |E|^2)k_0L \quad (3-12)$$

where $k_0 = 2\pi/\lambda$ and L is the fiber length. In the formula, the intensity-dependent nonlinear phase shift $\phi_{NL} = n_2 |E|^2 k_0L$, represents the self-phase modulation. Such a nonlinear phase shift plays an important role in generating new frequency components and leads to the spectrum broadening. On the other hand, the cross-phase modulation refers to the nonlinear phase shift of an optical field induced by another optical field

whose direction, polarization state or wavelength is different. The nonlinear phase shift of the field is expressed by:

$$\phi = \tilde{n}k_0L = n_2(|E_1|^2 + 2|E_2|^2)k_0L \quad (3-13)$$

in which the first term in the right of formula represents SPM, and the second term denotes XPM. Among the effects, due to the superimposed electric fields, XPM is responsible for an asymmetric spectral broadening.

3.2.1.3 Nonlinear Schrödinger Equation

When propagating along an optical fiber, an optical pulse with high intensity cannot avoid experiencing the chromatic dispersion as well as the nonlinear phase modulation. A general equation that includes all the effects is necessary to analyze the propagation of an optical pulse. The starting point is wave equation that is derived from the Maxwell equation.

$$\nabla^2 \tilde{E} + \varepsilon(\omega)k_0^2 \tilde{E} = 0 \quad (3-14)$$

where $\tilde{E}$ is the electric field of an optical pulse in frequency-domain whose mathematical expression is given by Eq. (3-5). By substituting Eq. (3-5) into Eq. (3-14) and applying the slowly varying envelope assumption, the wave equation of Eq. (3-14) can be separated into two equations, corresponding to the fields in the transverse and longitudinal directions, respectively [70]:

$$\frac{\partial^2 F}{\partial x^2} + \frac{\partial^2 F}{\partial y^2} + [\varepsilon(\omega)k_0^2 - \tilde{\beta}^2]F = 0 \quad (3-15)$$

$$i \frac{\partial \tilde{A}}{\partial z} + (\tilde{\beta} - \beta_0)\tilde{A} = 0 \quad (3-16)$$

In Eq. (3-15), the dielectric constant $\varepsilon(\omega)$ is given by:

$$\varepsilon = (n + \Delta n)^2 \approx n^2 + 2n\Delta n \quad (3-17)$$

where n and Δn are the linear and nonlinear refractive indexes described in Eq. (3-10). The solution $F(x, y)$ in Eq. (3-15) is the field-distribution of the fundamental mode with a propagation constant of $\beta(\omega)$. In the first-order perturbation theory [70], Δn does not influence the field-distribution $F(x, y)$. To simplify the equation, ε is replaced by n^2 in the first step. Then the effect of Δn is included into Eq. (3-15) to get the modified propagation constant:

$$\tilde{\beta}(\omega) = \beta(\omega) + \Delta\beta(\omega) \quad (3-18)$$

where

$$\Delta\beta(\omega) = \frac{\omega^2 n(\omega)}{c^2 \beta(\omega)} \frac{\int \int_{-\infty}^{\infty} \Delta n(\omega) |F(x, y)|^2 dx dy}{\int \int_{-\infty}^{\infty} |F(x, y)|^2 dx dy} \quad (3-19)$$

Since the actual functional forms of $\beta(\omega)$ and $\Delta\beta(\omega)$ are rarely known, it is helpful to use the expansion of Taylor series near the carrier frequency:

$$\begin{cases} \beta(\omega) = \beta_0 + (\omega - \omega_0)\beta_1 + \frac{1}{2}(\omega - \omega_0)^2 \beta_2 + \frac{1}{6}(\omega - \omega_0)^3 \beta_3 + \dots \\ \Delta\beta(\omega) = \Delta\beta_0 + (\omega - \omega_0)\Delta\beta_1 + \frac{1}{2}(\omega - \omega_0)^2 \Delta\beta_2 + \frac{1}{6}(\omega - \omega_0)^3 \Delta\beta_3 + \dots \end{cases} \quad (3-20)$$

The third-order and the higher-order terms of $\beta(\omega)$ can be neglected if the spectral bandwidth of the pulse satisfies the condition $\Delta\omega \ll \omega_0$. In the case of $\beta_2 \approx 0$, it is

necessary to include the third-order term. Under the same condition, we can apply the approximation:

$$\Delta\beta(\omega) \approx \Delta\beta_0 \quad (3-21)$$

By substituting Eq. (3-20) and Eq. (3-21) into Eq. (3-8) and taking the inverse Fourier transform, Eq. (3-16) can be further simplified. During the inverse Fourier-transform operation, $\omega - \omega_0$ can be changed by the differential operator $i \frac{\partial}{\partial t}$. Eq. (3-16) can be rewritten by:

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} = i\Delta\beta_0 A \quad (3-22)$$

in which

$$\Delta\beta_0 \approx \frac{\Delta n(\omega)\omega}{c} \quad (3-23)$$

By replacing the nonlinear refractive index $\Delta n(\omega) = n_2 |E|^2 + i\alpha/2$, in which includes the linear optical absorption α . Eq. (3-22) can be modified by:

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma(\omega_0) |A|^2 A \quad (3-24)$$

where

$$\left\{ \begin{array}{l} \gamma(\omega_0) = \frac{n_2(\omega_0)\omega_0}{cA_{eff}} \\ A_{eff} = \frac{(\int \int_{-\infty}^{\infty} |F(x, y)|^2 dx dy)^2}{\int \int_{-\infty}^{\infty} |F(x, y)|^4 dx dy} \end{array} \right. \quad (3-25)$$

in which the parameter $\gamma(\omega_0)$ is the nonlinear parameter. Since n_2 is related to the third-order susceptibility given by Eq. (3-11), γ in Eq. (3-25) denotes Kerr nonlinear effects. A_{eff} represents the effective mode area that is related to the mode-distribution $F(x, y)$. Since an optical pulse is moving at a group velocity of v_g , by doing the coordinate transformation:

$$T = t - z / v_g = t - \beta_1 z \quad (3-26)$$

Equation (3-24) can be further simplified by:

$$\frac{\partial A}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + \frac{\alpha}{2} A = i \gamma |A|^2 A \quad (3-27)$$

This equation is known as the generalized nonlinear Schrödinger equation (NLSE). Such NLSE could have an analytical solution that is in the similar form of the fundamental soliton. In the case of a fiber with anomalous dispersion ($\beta_2 < 0$), the expression of pulse $A(z, T)$ has a hyper-secant functional profile that is given by:

$$A(z, T) = \sqrt{\frac{|\beta_2|}{\gamma T_0}} \operatorname{sech}\left(\frac{T}{T_0}\right) \exp\left(\frac{iz}{2}\right) \quad (3-28)$$

in which the pulse duration is determined by $T_{FWHM} = 1.756T_0$ and the peak power of pulse is equal to $P_k = |\beta_2| / \gamma T_0$. It is noted that once the cavity parameters are given, the peak power of pulse is fixed.

3.2.1.4 Field-distribution of Propagation Mode

In order to calculate the field-distribution of the propagation mode $F(x, y)$, the propagation constant (β) of the guided mode in fiber should be determined. It starts from the wave equation given in Eq. (3-15):

$$\frac{\partial^2 F}{\partial x^2} + \frac{\partial^2 F}{\partial y^2} + [\varepsilon(\omega) k_0^2 - \beta^2] F = 0 \quad (3-29)$$

where $F(x, y)$ refers to either the distribution of the electric field components E or the magnetic field components H that propagates along the fiber. The wave number k_0 is defined as $2\pi/\lambda$ where λ denotes the wavelength. Due to the symmetrical geometry of SMF, the field distribution can be expressed with cylindrical coordinates:

$$F(r, \psi) = F(r) e^{im\psi} \quad (3-30)$$

The gradient operator in Cartesian coordinates is converted into the cylindrical coordinates by:

$$\nabla_i \vec{F} = \frac{\partial F}{\partial r} \vec{r} + r \frac{\partial F}{\partial \psi} \vec{\psi} \quad (3-31)$$

Therefore, the wave equation of Eq. (3-29) can be expressed as:

$$\frac{\partial^2 F}{\partial r^2} + \frac{1}{r} \frac{\partial F}{\partial r} + [n_i^2 k_0^2 - \beta^2 - \frac{m^2}{r^2}] F = 0 \quad (3-32)$$

in which n_i denotes the refractive index of the medium and $i = 1, 2$ represents core and cladding, respectively. Eq. (3-32) is a well-known differential equation for Bessel function having analytic solutions. In general, the solution in the core region as well as the cladding region can be given by:

$$F(r) = \begin{cases} J_m\left(\frac{U}{a}r\right) & r \leq a \\ K_m\left(\frac{W}{a}r\right) & r \geq a \end{cases} \quad (3-33)$$

where $J_m(x)$ and $K_m(x)$ represent Bessel function and modified Bessel function, respectively. U and W are the parameters related to the normalized frequency (V) which are given by:

$$\begin{aligned} U^2 &= (n_1^2 k_0^2 - \beta^2) a^2 \\ W^2 &= (\beta^2 - n_2^2 k_0^2) a^2 \end{aligned} \quad (3-34)$$

One can find that $U^2 + W^2 = (n_1^2 k_0^2 - n_2^2 k_0^2) a^2 = V^2$. Since the tangential components of E and H crossing over the core-cladding boundary should be continuous, it requires the field components at $r = a$ to satisfy the condition:

$$\begin{bmatrix} e_r \\ h_\psi \\ e_z \\ e_z \end{bmatrix}_{r=a_core} = \begin{bmatrix} e_r \\ h_\psi \\ e_z \\ e_z \end{bmatrix}_{r=a_clad} \quad (3-35)$$

The equality of these field components leads to an Eigen equation whose solution determines the propagation constant (β) of the fiber modes:

$$\beta^2 m^2 \left[\frac{1}{U^2} + \frac{1}{W^2} \right]^2 = \left[\frac{1}{U} \frac{J'_m(U)}{J_m(U)} + \frac{1}{W} \frac{K'_m(W)}{K_m(W)} \right] \left[\frac{k_0^2 n_1^2}{U} \frac{J'_m(U)}{J_m(U)} + \frac{k_0^2 n_2^2}{W} \frac{K'_m(W)}{K_m(W)} \right] \quad (3-36)$$

in which the prime represent the differentiation with respect to the argument. In general, for each m value, there might be several solutions of β . β_{mn} is included to distinguish each fiber mode, in which m and n take integer values.

Once propagation constant β is known, the field-distribution of propagation mode $F(x, y)$ can be derived by Eq. (3-33) and Eq. (3-34).

3.2.2 Pulse Propagation in Gain Fibers

Gain fibers are designed to compensate for loss and restore signal in the long-haul transmission link by doping rare-earth elements into the fiber. The main elements selected in silica fibers are erbium, ytterbium, and thulium with the corresponding operation wavelengths of 1.55, 1, and 2 μm , respectively. In particular, the erbium-doped fibers have attracted extensive attention because their useful applications being amplifiers in modern fiber optic communication systems.

Figure 3-3 Schematic diagram of energy level of an erbium-doped fiber

The doped fiber can be modeled by a two-level pumping scheme in which only two energy levels involves in light-induced transition [71]. Fig. 3-3 shows the schematic diagram of light amplification in a two-level system. In order to achieve that the stimulated emission is stronger than absorption, optical pumping is necessary to create a

population inversion between the two energy levels. Such population inversion provides the optical gain with a gain coefficient:

$$g = \sigma(N_2 - N_1) \quad (3-37)$$

in which σ is the transition cross section, N_1 and N_2 denote atom densities in the two-energy levels. For an ideal homogenously broadened gain medium, the gain coefficient can be written as [71]:

$$g(\omega) = \frac{g_0}{1 - (\omega - \omega_g)^2 T_2^2 + P/P_{sat}} \quad (3-38)$$

in which g_0 is the maximum small signal gain in the gain medium, ω is the frequency of incident light, ω_g is atomic transition frequency, T_2 is known as the dipole relaxation time, P is the power of incident light, and P_{sat} is the saturation power that depends on the dopant. Considering that the gain medium operates in an unsaturated regime $P/P_{sat} \ll 1$, Eq. (3-38) can be rewritten by:

$$g(\omega) \approx g_s(\omega) \times \tilde{g}_f(\omega) = \frac{g_0}{1 + P/P_{sat}} \times \frac{1}{1 - (\omega - \omega_g)^2 T_2^2} \quad (3-39)$$

From Eq. (3-39), one can find that the gain coefficient consists of two parts: the first part $g_s(\omega)$ is power-dependent which is responsible for the gain saturation, while the second part $\tilde{g}_f(\omega)$ is frequency-dependent which is responsible for gain dispersion or gain bandwidth. The two properties differentiate the gain fibers from the standard SMFs.

When an optical pulse propagates along a gain fiber, ignoring the dispersion, the nonlinearity and the noise, the pulse envelope of pulse $A(z, T)$ is reshaped by:

$$\frac{\partial A(z, T)}{\partial z} = \frac{1}{2} \int_{-\infty}^{\infty} g(T - t_1) A(z, t_1) dt_1 \quad (3-40)$$

The influence of the gain saturation as well as gain dispersion on $A(z, T)$ will be discussed in the following sections.

3.2.2.1 Gain Saturation

Due to the finite density state of the upper energy level, the population inversion of a gain medium is limited even if the pump is at a relatively high power level. In such case, the gain medium cannot provide more amplification for a given incident power and the resultant output power is typically a constant, known as gain saturation.

When an optical pulse with a short pulse duration passing through a rare-earth doped fiber, since the upper state lifetime T_1 in the gain medium is around $\sim 1\text{ms}$, the gain saturation can be neglected within the single pulse duration. However, the gain saturation cannot be omitted in the situation when a pulse sequence has the timescales longer than T_1 . In such case, the saturated gain $g_s(z)$ is related to the average power (P_{ave}) of pulse sequence which can be written as:

$$g_s(z) = \frac{g_0(z)}{1 + P_{ave}(z)/P_{sat}} \quad (3-41)$$

where

$$P_{ave}(z) = \frac{1}{T_m} \int_{-T_m/2}^{T_m/2} |A(z, T)|^2 dT \quad (3-42)$$

in which T_m is the pulse-to-pulse separation and it is inversely proportional to the repetition rate of the pulse sequence.

3.2.2.2 Gain Dispersion

The gain dispersion is the phenomenon in which the incident beams with various frequencies obtain different optical gains, which is due to the uneven gain spectrum. To find out the gain dispersion, the gain spectrum should be known. As described in Eq. (3-39), the frequency-dependent gain coefficient $\tilde{g}_f(\omega)$ takes a Lorentzian profile:

$$\tilde{g}_f(\omega) = \frac{1}{1 - (\omega - \omega_g)^2 T_2^2} \quad (3-43)$$

in which the frequency ω of incident light is near the transition frequency ω_g . Regardless of the profile chosen, the gain spectrum can always be expanded by a Taylor series:

$$\tilde{g}_f(\omega) \approx 1 - (\omega - \omega_g)^2 T_2^2 \quad (3-44)$$

From above formula, one can find that the gain spectrum approaches a nearly-parabolic profile and exhibits a limited gain bandwidth which is approximated to be $1/(\pi T_2)$. When an optical pulse is passing through a rare-earth doped fiber, by taking into account the finite gain bandwidth, the pulse envelope $A(z, T)$ in Eq. (3-40) can be modified by:

$$\begin{aligned} \frac{\partial A(z, T)}{\partial z} &= \frac{1}{2} f^{-1} \{ A(z, \omega - \omega_0) \bullet g(\omega) \} \\ &= \frac{g_s(z)}{2} f^{-1} \{ A(z, \omega - \omega_0) \bullet \tilde{g}_f(\omega) \} \\ &= \frac{g_s}{2} [A(z, T) + T_2^2 \frac{\partial^2 A(z, T)}{\partial T^2}] \end{aligned} \quad (3-45)$$

For the inverse Fourier-transform operation, $\omega - \omega_0$ can be substituted by the differential operator $i \frac{\partial}{\partial T}$. It is noted that Eq. (3-45) is only valid if the center frequency ω_0 of the pulse is close to the transition frequency ω_g .

3.2.2.3 Ginzburg-Landau Equation

When an optical pulse propagates along a gain fiber, in addition to the effects of gain saturation and gain dispersion, the effects of chromatic dispersion and nonlinearity need to be taken into account.

Differing from the standard SMF, the parameter values in the gain fiber have a complicated dependence if the medium is pumped. However, the values should be fixed for a given set of parameters. To be simplicity, the effects of gain can be added together by incorporating Eq. (3-45) into Eq. (3-27) [71]:

$$\frac{\partial A}{\partial z} + \frac{i}{2}(\beta_2 + ig_s T^2) \frac{\partial^2 A}{\partial T^2} + \frac{1}{2}(\alpha - g_s)A = i\gamma |A|^2 A \quad (3-46)$$

The developed equation is known as Ginzburg-Landau Equation (GLE), which can be used to solve the pulse propagation along a gain fiber. When set $g_s \rightarrow 0$, it is found that GLE is changed back to NLSE as given in Eq. (3-27). In the case of a fiber with anomalous dispersion ($\beta_2 < 0$), the general solution of Eq. (3-46) can be approximated by a chirped hyper-secant functional profile written by:

$$A(z, T) = a \operatorname{sech}\left(\frac{T}{T_0}\right)^{1+iq} \exp(ikz) \quad (3-47)$$

in which a , T_0 , k can be derived from the cavity [71]. The above preserving shape of pulse is known as the dissipative soliton. The main characteristic of dissipative soliton in contrast to the conventional soliton is that the dissipative soliton is highly frequency-chirped, which enables the pulse to attain a relatively high pulse energy without pulse-breaking.

So far, NLSE and GLE are derived to describe pulse propagation along a passive fiber and an active fiber, respectively. The suggested analytical solutions, however, are only valid to some cases that the third-order dispersion and noise are ignored. In most situations, the two equations need to be solved numerically when the high-order dispersion needs to be taken into account. The well-known algorithm to solve the nonlinear partial differential equation is the split-step Fourier method (SSFM) [70]. In the following, the procedure to solve GLE by SSFM is introduced. It also can be a general guidance to solve the NLSE because NLES is just a simplified GLE by setting the gain coefficient to zero.

Figure 3-4 Illustration of the split-step Fourier method.

The core idea of SSFM to solve GLE is based on the assumption that the fiber dispersion and the fiber nonlinearity act independently, as shown in Fig. 3-4. To be more clearly, it is useful to rewrite the GLE as:

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N}) A \quad (3-48)$$

in which D is the differential operator that is responsible for fiber dispersion, gain and loss, while N is the differential operator that is responsible for fiber nonlinearity consisting of self-phase modulation. They are defined as:

$$\begin{cases} \hat{D} = -\frac{i}{2} \beta_2 \frac{\partial^2}{\partial T^2} + g_s T_2^2 \frac{\partial^2}{\partial T^2} + \frac{1}{2} (g_s - \alpha) \\ \hat{N} = i\gamma |A|^2 \end{cases} \quad (3-49)$$

For pulse propagates over a very small step $\Delta z = h$, the exact solution of Eq. (3-48) is given by:

$$A(z+h, T) = \exp[h(\hat{D} + \hat{N})] A(z, T) \quad (3-50)$$

As shown in Fig. 3-4, in the first half distance, it only considers D by setting $N = 0$, which is also treated in a similar way for the rest half distance. In the middle of the step, only the operator N is taken into account. Hereby, Eq. (3-50) is revised to be:

$$A(z+h, T) \approx \exp\left(\frac{h}{2} \hat{D}\right) \exp\left(\int_z^{z+h} \hat{N}(z') dz'\right) \exp\left(\frac{h}{2} \hat{D}\right) A(z, T) \quad (3-51)$$

A comparison of Eq. (3-50) to Eq. (3-51) shows that the SSFM omits the non-commutating nature of the operators D and N . Therefore, the SSFM is accurate to second-order in the step size h [70]. The merit of SSFM is that it has less computation

time to solve GLE because the differential operator D can be solved in frequency-domain rather than it is calculated in time-domain by using FFT and IFFT algorithm.

3.3 Theoretical Model of Pulse Shaping by Saturable Absorbers

When a saturable absorber is incorporated into a laser cavity, the cavity loss can be self-modulated since light with low intensity suffers high loss but light with high intensity experiences low loss. Such a decrease of cavity loss can assist a laser to produce optical pulses within the time window when the gain is greater than the cavity loss. In other words, an optical pulse is superior to continuous wave to be existed in the laser cavity due to the relatively minor loss when a SA opens. The recovery time of a saturable absorber determines the net gain window, therefore, it influences on the pulse shaping. Assuming that there is no change of dispersion and refractive index in a laser system, a slow SA with a recovery time longer than pulse duration tends to broaden the trailing edge of the pulse, as shown schematically in Fig. 3-5. In general, a fast SA is always desirable in a laser system to obtain the ultrashort pulse. With the inclusive of the dispersion and nonlinearity-induced soliton shaping, the pulse width could be further compressed below the net gain window.

Figure 3-5 Schematic diagram of pulse reshaping by fast and slow SAs.

Theoretical models can be built to simulate the function of slow and fast SAs. When an optical pulse passes through a SA, the absorption coefficient α can be written as:

$$\alpha = \alpha_{ns} + \alpha_s \quad (3-52)$$

in which α_s is the saturable absorption coefficient that is dependent on either the pulse energy or the peak power of pulse. α_{ns} is the non-saturable absorption coefficient that is related to the intrinsic loss of a SA. For a SA with slow response time, the saturable absorption coefficient satisfies the following rate equation [72]:

$$\frac{d\alpha_s(z, T)}{dT} = -\frac{\alpha_s - \alpha_0}{\tau_{sa}} - \alpha_0 \frac{|A(z, T)|^2}{E_{sa}} \quad (3-53)$$

where α_0 is the modulation depth, τ_{sa} is the recovery time, and $E_{sa} = P_{sa} \tau_{sa}$ is the saturation energy. P_{sa} is the saturation power of a SA. By considering $\tau_{sa} \rightarrow 0$, the

solution of Eq. (3-53) is an exact expression of α_s for a SA with fast response time, which can be expressed as:

$$\alpha_s(z, T) = \frac{\alpha_0}{1 + |A(z, T)|^2 / P_{sa}} \quad (3-54)$$

From Eq. (3-53) and Eq. (3-54), one can find that a slow SA saturates with the pulse energy in comparison with a fast SA that saturates with the peak power of the pulse.

In the case of CNT-based SAs, in addition to recovery time, saturable absorption, and non-saturable absorption, the thermal conductivity of CNTs should be considered. Experimental reports show that an optical pulse with high intensity could cause thermal damage to CNTs. Previous reports have conducted thermal characterization of CNT bundles using self-heating technique [73]. It is found that CNT bundles have the average thermal diffusivity around $1.74 \times 10^{-5} \text{ m}^2/\text{s}$ which is much less than the thermal diffusivity of bulk graphite. Such low thermal diffusivity can be explained by the possible structural defects of CNTs, the random orientation of CNTs in the bundle and the thermal contact resistance between CNT threads. Therefore, in order to mitigate the optical heating induced thermal damage of CNTs for practical implementations, both the quality of CNTs and the intensity of incident light should be well managed.

So far, theoretical models of pulse propagation along passive fibers, active fibers, and saturable absorbers have been introduced, which form the bases for analyzing pulse propagation in mode-locked fiber lasers. Then, the numerical model of soliton fiber laser will be discussed.

3.4 Theoretical Model of Mode-locked Fiber Lasers

3.4.1 Conditions for Mode-locking

The previous sections review the localized effects when an optical pulse passes through individual component including a standard SMF, a gain fiber, and a saturable absorber. In this section, all the components are treated as a unit to construct a semi-close-loop laser oscillator as schematically shown in Fig. 2-9. Even though two fiber lasers have exactly the same cavity layout, their operation states could be much different: either mode-locking or Q-switching which mainly depends on the intra-cavity pulse energy. Generally, the condition for a fiber laser working in CW mode locking rather than Q-switching can be expressed as [74]:

$$E_p^2 > E_{sat,g} E_{sa} \alpha_0 \quad (3-55)$$

Where E_p refers to the pulse energy, $E_{sat,g}$ and E_{sa} demote the saturation energy of gain fiber and saturable absorber, respectively. α_0 represents the modulation depth of a saturable absorber. From the formula, with a given modulation depth of a saturable absorber, both a lower value of $E_{sat,g}$ and E_{sa} improve the self-starting capability of laser to be mode-locked.

3.4.2 Master Equation for Mode-locked Fiber Lasers

Once the pulse energy is above threshold described in Eq. (3-55), all the linear and nonlinear effects originated from the individual component contribute to the final steady-state pulse formation. By assuming that the linear and nonlinear changes of a pulse within one round-trip time in a laser cavity are small, a master equation including

all effects can be established to describe the pulse formation in a mode-locked laser. The equation is proposed by Huas' group [49], and written by:

$$T_R \frac{\partial A}{\partial T} + \frac{i}{2} (\bar{\beta}_2 + i \bar{g} T_R^2) L_R \frac{\partial^2 A}{\partial t^2} = i \bar{\gamma} L_R |A|^2 A + \frac{1}{2} (\bar{g} - \bar{\alpha}) L_R A - \frac{\alpha_0/2}{1 + |A(T, t)|^2 / P_{sa}} A \quad (3-56)$$

in which the overbar of $\bar{\beta}_2, \bar{\gamma}, \bar{g}, \bar{\alpha}$ denote the average values of the corresponding parameters in the laser cavity. L_R refers to the cavity length, T_R represents cavity round-trip time, and they have the relationship of $T_R = L_R / v_g$ (v_g refers to the group velocity of the pulse). One can find that master equation is quite similar to the GLE as given in Eq. (3-46), so the Master equation can be solved numerically by SSFM. Indeed, the Master equation can be derived from the GLE by including the effect of a SA and changing the coordinates from $A(z, T)$ to $A(T, t)$ through:

$$\begin{cases} t = T \\ T = z/v_g \end{cases} \quad (3-57)$$

It is important to note that there are two time-scales in Master equation: t refers to the frame of moving pulse and T presents the propagation time. Since t is generally far smaller than T , the two time-scales can be decoupled. The Master equation is valid to a range of mode-locked lasers in which the dispersive and nonlinear changes to pulse are continuously distributed and can be considered as an average effect. However, in a real laser system, different types of elements construct a laser cavity and show a discrete distribution of the linear and nonlinear changes. Such discrete effects will induce the pulse to encounter more loss than that from the continuous distribution. Therefore, the pulse dynamic in the localized position should be taken into account.

In this thesis, we focus on a localized effect instead of taking an average effect. A typical program flow is shown in Fig. 3-6, in which the model of each fiber element is based on either NLES given in Eq. (3-27) or GLE described in Eq. (3-46).

Figure 3-6 Program flow of passively mode-locked fiber lasers.

3.5 Summary

This chapter includes the theoretical framework necessary to describe passively mode-locked fiber lasers. The nonlinear Schrödinger equation and Ginzburg-Landau equation are derived to describe pulse propagation in passive fibers and active fibers, respectively. The SSFM to solve the equations have been included. The model of SAs is also introduced. In the last part of this chapter, the program flow to analyze the mode-locked fiber lasers is given.

Chapter 4 Fabrication of Carbon-Nanotube-Based Devices

This chapter mainly presents the methodologies to integrate CNTs with optical fibers for carbon-nanotube-based devices. The methods include mechanical spray, optically-driven deposition, and chemical vapor deposition. The details of CNT integration process for each method are given together with the characterization of the fabricated CNT-based devices.

4.1 Introduction

CNTs being nano-materials needs to be integrated with optical waveguides for CNT-based devices in order to establish light-CNT interaction. The optical fiber is the mostly targeted waveguide since it enables CNT-based devices to be consistent with the entire fiber link. By integrating CNTs with standard SMFs or specialty fibers, CNT-based fiber devices can meet various requirements in practical application such as high nonlinearity [75, 76], desirable optical absorption [69] insensitive to polarization [36, 77], and high thermal damage threshold [32]. A couple of methods have been demonstrated to integrate CNTs with optical fibers including mechanical spray [32, 36, 75, 76], polymer composition [34, 53, 69], optically-driven deposition [27, 28, 30, 78-80], and CNT-layer transfer [81]. Each method can offer several advantages in terms of the mass production, the ease of handling, the efficient in-use of CNTs, the controllable deposition process, and the well-alignment of tubes.

In this chapter, besides the convention mechanical spray method to fabricate CNT-based devices, we track and validate the method of optically-driven deposition of CNTs

onto standard SMFs. Moreover, we extend the optically-driven deposition method to special optical fibers including tapered fibers and side-polished fibers in order to enhance the thermal damage threshold of CNT-based devices. By controlling the incident power and time duration in the optically-driven deposition process, CNT-layers in a ring pattern can be deposited onto the end-face of a standard SMF. The inner ring diameter of CNT-layer is found to be power-dependent in the deposition process. By designing the taper diameter, tapered fibers are coated with CNT-layer showing a better smoothness than those in previous reports. Through the optimization of the polished depth, side-polished fibers are coated with thin CNT-layers by optically-driven deposition method for the first time. In addition to above two methods, we demonstrate the possibility of direct growth of vertically-aligned CNTs on side-polished fibers by chemical vapor deposition (CVD) technique for the first time. The details of CNT integration process by each method as well as the characteristics of the prepared CNT-based devices are included.

4.2 Mechanical Spray Method

The method of mechanical spray to fabricate CNT-based devices is typically using spray gun to spout out the solution-dispersed CNTs onto targets. This method has a number of advantages including: (i) easy handling; (ii) no extra complicated equipment; (iii) the deposited CNT-layer has relatively good uniformity; and (iv) mass production. To conduct the mechanical spray, CNT powders should be well dispersed in solution.

The CNT powder in the experiment is provided by the collaborators of The University of Tokyo, Japan. Such CNTs are made by a bulk production method called high-pressure CO conversion (HiPCO). By controlling the HiPCO process and the resultant the nanotube diameters, the optical absorption property of CNTs can be controlled. Although HiPCO is an efficient method to synthesize semiconducting CNTs with high purities, there are still a small portion of multi-walled CNTs and metallic CNTs mixed with semiconducting CNTs. In order to select the wanted CNTs, the synthesized CNT powders are further dispersed in dimethylformamide (DMF) solvent for purification process. DMF is chosen as dispersant due to the capability of overcoming the strong van der Waals force between CNTs thereby it guarantees CNTs with homogenous and relatively aggregate-free distribution [82, 83]. Ultrasonic is conducted to break up the largest aggregations and remove the catalyst residuals. Centrifugal separation is then performed to purify the solvent by mass difference. After CNT purification process, only the homogeneous part is taken as shown in Fig.4-1(a).

Figure 4-1 (a) Photo of CNTs dispersed in DMF solution and (b) optical absorption of CNT solution.

As the purification process removes a number of the aggregated CNTs, it is difficult to estimate the actual CNT concentration in DMF solution. However, we can maintain the quality of CNTs in DMF solution by keeping the same absorption of the prepared solution. Fig. 4-1(b) plots the absorption spectrum of CNTs in DMF solution measured by a spectrophotometer. The CNT solution maintains the optical absorption of ~20% ranging from 900 nm to 1700 nm, showing a desirable absorption peak near C-band. According to the relationship between absorption peak and nanotube diameter as shown in Fig. 2-3, the average diameter of CNTs after purification process is around 1 nm.

Figure 4-2 Microscopic images of fiber ends deposited with CNTs by mechanical spray method (a) without and (b) with the dryer heating.

Subsequently, a certain volume of the prepared CNT solution is injected into a spray gun pumped with N_2 gas. By manipulating a valve for pumping the fluid flow, CNTs can be sprayed onto targets. A number of fiber patch cords are fixed on holders with the end-facts facing the fluid. The spray coating lasts for 5 seconds and this process is repeated by 3 times. Fig. 4-2(a) shows the microscopic image of end-facet of optical fiber after CNT deposition. A layer of CNTs is deposited on fiber core region. However, the

residual DMF solution is also coated on the core region that might degrade the performance of CNT-based device. In order to reduce the residual DMF solution coated on fiber end, a dryer to heat up the solution is employed simultaneously during the spray coating. Fig. 4-2(b) shows the microscopic image of end-facet of fiber by spray coating with dryer heating. A layer of CNTs with a better uniformity are coated on fiber end in comparison to the one without dryer heating. By using this methodology, the finished CNT-based fiber devices show an insertion loss ranging from 1 to 4 dB.

The spray method is a relatively easy way to deposit CNTs on fiber for CNT-based device. However, the controllability of CNT distribution in a small scale is hardly achieved by spray-coating method since CNT solution is sprayed on targets in a large area. In addition, a large amount of CNTs is deposited outside the target that is wasted during the coating process.

4.3 Optically-driven Deposition Method

Optically-driven deposition of CNTs refers to manipulate CNT particles onto targets by using optical beam. The advantages of this method to fabricate CNT-based devices include the relatively controllable process in which CNTs are only deposited onto the targeted area and the efficient in-use of CNTs [27, 28, 30, 77-80, 84]. In this section, we systematically investigate the fabrication of CNT-based devices by using optically-driven deposition method. In order to construct fiber-end-type CNT-based devices, CNTs are optically deposited onto end-faces of standard SMF. Particularly, CNTs can be formed in a ring pattern on the fiber end to achieve functional devices. In order to

construct CNT-based devices for CNT-light interaction in a long distance, specialty fibers including tapered fibers and side-polished fibers are designed as the host waveguides.

4.3.1 CNT Deposition on End-facet of Optical Fiber

Figure 4-3 Illustration of CNT deposition onto end-facet of optical fiber in the presence of optical radiation.

The schematic diagram of CNT deposition on end-facet of optical fiber in the presence of optical radiation is illustrated in Fig. 4-3. The movement of CNTs suspended in solution towards the connector end could be explained by thermophoresis, in which the temperature gradient is caused by heating due to optical absorption [27]. Furthermore, the formation of CNTs in a ring pattern on the end-facet of the connector is believed to be a result of balance between the scattering force and the gradient force generated by the optical radiation [27, 28]. Such gradient force attracts CNT particles in the direction

of increasing intensity while the scattering force pushes CNT particles in the direction of propagation. Because of the divergence of the optical radiation in a standard SMF [85], the gradient force is insufficient to overcome the scattering force. As the radiation field distribution is circularly symmetric, a ring pattern of CNTs can be formed around the core region. In general, a higher optical power is required to form a larger inner diameter through a stronger scattering force, while the duration of deposition controls the outer ring diameter and the resultant layer thickness.

Figure 4-4 Experimental setup for in-situ monitoring of CNT deposition on fiber end by optically-driven deposition method: laser diode (LD); erbium-doped fiber amplifier (EDFA).

Fig. 4-4 shows the typical experimental setup for CNT deposition on fiber end. A seeded light from a continuous-wave (CW) 1.55- μm laser diode (LD: AQ8201-13A) is amplified by an erbium-doped fiber amplifier (EDFA: CEFA-C-PB-SM-33). A fixed connection/physical contact (FC/PC) connector guides the light into the prepared CNT solution as described in above section. An optical circulator is inserted before the connector for collecting the reflected light and protecting the light source. A power meter (MT9810A) to measure the fluctuation of reflected power is used in order to in-situ monitor the CNT deposition process.

4.3.1.1 CNT Deposition on Core Region

Figure 4-5 Measurement of reflectivity against deposition time.

During CNT deposition process, when EDFA is turned on below a power level of ~ 19 dBm, there is no significant change of reflected power. Above 19 dBm, a dramatic increase of 21 dB in reflectivity is observed as shown in Fig. 4-5. Generally, the reflectivity (R) at the interface of two mediums can be estimated by Fresnel reflection equation Eq. (4-1):

$$R = \frac{P_{ref}}{P_{in}} = 10 \log_{10} \left(\frac{n_0 - n_1}{n_0 + n_1} \right)^2 (dB) \quad (4-1)$$

where P_{in} and P_{ref} are input power and reflected power, respectively. n_0 and n_1 are refractive indexes of fiber and the ambient, respectively. The 21-dB enhancement of R in the experiment indicates that the fiber end ($n_0 \approx 1.45$) is changed from being surrounded by the DMF ($n_1 \approx 1.42$) solution only to being coated with CNTs ($n_1 \approx 3$)

[86]. After an observation of 21-dB enhancement in reflectivity, we maintain the fiber connector end in the prepared CNT solution for an additional 2 minutes until the fluctuation of R becomes small and then we take it out from the solution. Fig. 4-6(a) shows the microscopic image of fiber end after CNT deposition under the incident powers of ~ 19 dBm. One can find that a layer of CNTs covers the core region of fiber end. In contrast to the spray method, CNTs are only deposited onto the targeted region by optically-driven deposition method which achieves the efficient in-use of CNTs.

Figure 4-6 Microscopic images of fiber ends deposited with CNTs on core region under incident powers of (a) 19 and (b) 19.5 dBm.

Since the movement of CNTs is triggered by the incident light, we have investigated the influence of incident power on the formation of CNTs on fiber ends. We find that the power margin for CNT deposition onto fiber core region is relatively small for the prepared CNT solution. When the incident power is at ~ 19.5 dBm, CNTs can still be deposited onto the core region whose microscopic image is shown in Fig. 4-6(b). With a higher incident power than 19.5 dBm, CNTs are frequently deposited around the fiber end rather than on the core region, which will be described in the next section.

4.3.1.2 CNT Deposition around Core Region

Figure 4-7 Microscopic images of fiber ends deposited with CNTs around core region with the inner ring diameters of (a) 10, (b) 12, (c) 14 and (d) 38 μm .

Under a high power, ring pattern of CNTs is expected to be formed on fiber ends [28]. Practically, CNT-layer in ring pattern can be reproduced with similar setup and CNT solution. Figs 4-7(a)-(d) show the microscopic images of end-facet of fiber after CNT deposition when the incident powers are 20, 20.5, 20.7, and 22 dBm, respectively. We can obtain deposited CNT-layer in ring pattern with an inner ring diameter of 10, 12, 14

and 38 μm , correspondingly. The results further verify that the strong scattering force pushes CNT particles away from the core region. Such ring pattern of CNTs is very useful to enhance the thermal damage threshold of CNT-SAs, which will be introduced in Chapter 5.

4.3.2 CNT Deposition on Sidewall of Optical Fiber

In above sections, we have demonstrated CNT deposition onto end-facets of standard SMFs to construct fiber-end-type CNT-based devices. In some applications, in order to meet the requirement of CNT-based devices, for instance, high nonlinearity [75, 76] and desirable optical absorption [69], CNT deposition along specialty fibers for long-distance CNT-light interaction is necessary. The working mechanism of such kinds of CNT-based devices is generally based on evanescent-field interaction. The targeted fibers are typically tapered fibers or side-polished fibers, because CNTs can be deposited onto the outer surface of these fibers without breaking up the fibers. Next, we numerically optimize the parameter of tapered fibers and side-polished fibers, and experimentally fabricate CNT-based devices by optically-driven deposition method.

Figure 4-8 Illustration of CNT deposition onto sidewall of optical fiber in the presence of evanescent field.

For optically-driven deposition of CNTs in the presence of evanescent field, the movement of CNTs suspended in solution towards fiber sidewall is dominated by thermophoresis and gradient force as schematically shown in Fig. 4-8. Particularly, the evanescent field with an intensity gradient on fiber surface creates a radial potential in transverse plane, which results in a dipole force to trap dielectric particles towards fiber side-surface [87].

(a)

(b)

Figure 4-9 Experimental setup for CNT deposition on tapered fibers or side-polished fibers, (a) schematic diagram: laser diode (LD); erbium-doped fiber amplifier (EDFA); polarization controller (PC), and (b) photo of a tapered fiber on translation stage for CNT deposition.

Fig. 4-9(a) shows the schematic diagram of an experimental setup for CNT deposition onto sidewall of tapered fibers as well as side-polished fibers. A seeded light from a CW 1.55- μm LD is amplified by an EDFA. A polarization controller (PC) is used to adjust

the polarization state of the incident light. A pair of V-groove fiber holders horizontally fixes the pigtails of specialty fibers, while the middle part of specialty fibers is initially suspended in air. During CNT deposition process, the middle part of specialty fibers is immersed into a volume of the prepared CNT solution that is supported by a quartz plate through the surface tension force. A power meter measuring the power fluctuation at fiber output port is included in order to monitor CNT deposition process. The photo of a fiber on the translation stage is shown in Fig. 4-9(b).

4.3.2.1 CNT Deposition on Tapered Fiber

By pulling a standard SMF with the diameter down to several micrometers, mode broadening happens in the tapered fiber in which the evanescent field penetrates into surroundings. Such an evanescent field can interact with CNTs for CNT-based devices as schematically shown in Fig. 4-10. Three parameters are involved to identify a tapered fiber including the transition slope S (refers to the change in the taper radius per unit length), taper diameter d_w , and taper length L . Provided that the majority of optical power in tapered fibers is confined in the fundamental mode and not be coupled to a higher-order mode, the tapered fibers are considered adiabatic where the transition slope S has to be small. Under this criterion, only the taper diameter d_w and the taper length L determine the performance of CNT-based devices.

Figure 4-10 Schematic diagram of CNT deposition on a tapered fiber.

Figure 4-11 Calculation of mode broadening in tapered fibers against taper diameter.

Since the geometries of the core and the cladding of a fiber are reduced proportionally during fiber tapering process, the original core is almost vanished once the diameter of fiber is tapered down to several micrometers. Hence, the original cladding could dominate the wave propagation and becomes the core. Fig. 4-11 calculates the optical power penetrating into surroundings in the relationship of taper diameter before the tapered fibers are deposited with CNTs. In order to calculate the percentage of optical power outside the tapered fiber, the field-distribution of propagation mode should be

determined. Such field distribution can be derived from the Eigen-equations described in section 3.2.1.4. Here, the core region is replaced by silica glass ($n_1 = 1.45$), and air becomes the cladding ($n_2 = 1$). The obtained figure clearly shows that the leakage power sharply increases when the taper diameter is less than $\sim 4 \mu\text{m}$ with mode profile given in the inset of Fig. 4-11. In other words, a smaller taper diameter can promise a higher optical absorption by the coated CNTs within a relatively short interaction distance. On the contrary, the taper fiber with a smaller taper diameter typically requires a longer taper length in order to satisfy the adiabatic criterion. However, such taper fibers are mechanically fragile, which increases the degree of difficulty of handling the fibers in practical applications. In order to strengthen the robustness of the device, the taper diameter is optimized to be $9 \mu\text{m}$ in this work.

In the experiment, the fabrication of tapered fibers is done by heating the standard SMF using a flame together with the mechanical pulling. The taper diameter of the finished fibers is controlled to be $\sim 9 \mu\text{m}$ with an insertion loss of 1 dB in air. Subsequently, the tapered fiber is fixed on V-groove fiber holders for CNT deposition. When the tapered fiber is surrounded by CNT solution, an additional 4.5-dB loss is observed with a low incident power level. By adjusting the incident power to be ~ 14 dBm, the transmission of the tapered fiber drops by 3.5 dB. The additional 3.5-dB optical absorption implies that CNTs are coated around tapered fiber. Then we switch off light source and remove the fiber from CNT solution. Fig. 4-12 shows the microscopic images of the fabricated CNT-deposited tapered fiber. One can observe that the CNT distribution around the taper fiber is very uniform, which is quite different from

the aggregated distribution of CNTs shown in previous reports [77, 84]. We find that the flatness control of tapered fiber surface and the dispersion control of CNT particles in CNT/DMF solution are essential for the uniform distribution of the deposited CNT-layer on fiber. The total length of CNT-layer deposited on the tapered fiber is around ~ 6.6 mm that is comparable to the width of quartz plate. The thickness of the CNT-layer is $\sim 1\mu\text{m}$. Due to the long-distance CNT-light interaction, the minimum insertion loss of the CNT-deposited tapered fiber we can obtain in the experiment is around ~ 6 dB.

Figure 4-12 Microscopic images of tapered fiber with taper diameter of $\sim 9\mu\text{m}$ deposited with CNTs at (a) left edge, (b) middle region and (c) right edge.

4.3.2.2 CNT Deposition on Side-polished Fiber

Unlike tapered fibers with the entire modification of the fiber core and cladding, only a part of cladding is removed in side-polished fibers. CNTs can be deposited on the side-polished surface for evanescent-field interaction. The key parameter to determine the performance of side-polished fibers is the polished depth d_p as shown schematically in Fig. 4-13. Provided that the polished surface is flat, the single-mode condition can be maintained and no higher-order is excited in side-polished fibers. When the polished surface is close to the core region and coated with CNTs, the mode can be broadened and penetrate into the CNT-layer. A larger polished depth is responsible for a larger optical attenuation coefficient.

Figure 4-13 Schematic diagram of CNT deposition on side-polished fiber.

Fig. 4-14 calculates the optical transmission of 1-mm-long side-polished fiber coated with CNTs in the relationship of the polished depth. The theoretical model of side-polished fiber is based on mode coupling between the fundamental mode of SMFs and the radiation modes in external medium [88], and formula of the attenuation coefficient is given in appendix A. The figure clearly shows that the optical transmission of a side-polished fiber is sharply decreased when the polished depth is larger than $\sim 57.2 \mu\text{m}$. At

the turning point of the curve, the distance from the polished surface to the center is estimated to be around ~ 1.2 times larger than the core radius. The corresponding mode distribution is shown in the inset of Fig. 4-14. Due to an asymmetric structure, the CNT-deposited side-polished fiber could be polarization-sensitive depending on the polished depth. In order to minimize the polarization sensitivity as well as achieve the desirable optical absorption, the polished depth is optimized to be $\sim 57.2 \mu\text{m}$ in this work.

Figure 4-14 Calculation of mode broadening in side-polished fiber against polished depth.

Figure 4-15 Microscopic images of side-polished fibers (SPFs) at (a) transition region, deposited with CNTs showing an insertion loss of (b) 1.2 and (c) 1.4 dB.

The side-polished fibers in the experiment are purchased from Phoenix Photonics Limited (United Kingdom), having a polished depth of $\sim 57.2 \mu\text{m}$ and a polished length of $\sim 1.7 \text{ cm}$. As the evanescent-field is penetrating into surrounding in one direction, the power threshold for triggering CNT movement towards sidewall of side-polished fiber is believed to be higher than that of tapered fiber. Experimentally, the power threshold is found $\sim 19 \text{ dBm}$. Under this power level, the transmission of the fiber decreases around $\sim 1 \text{ dB}$ with a deposition duration of ~ 30 minutes. Fig. 4-15 shows the microscopic

images of two side-polished fibers deposited with CNTs under similar condition, where CNT-layers are successfully coated on fiber sidewall. The obtained CNT-deposited side-polished fibers have a total insertion loss less than 2 dB. It is worth mentioning that this is the first time to demonstrate CNT deposition on side-polished fiber by optically-driven deposition method.

4.4 Chemical Vapor Deposition (CVD) Method

The fabrication of CNT-based devices described above is in general randomly depositing CNTs on waveguides without any alignment. However, theoretical analysis has predicted that light absorption or optical excitation of CNTs can be maximized when the electric field is parallel to the tube axis [89]. As shown in Fig. 4-16, LP_{01} -Y mode is highly absorbed by CNT when incident light is in z-direction. Such anisotropic absorption characteristics of CNT could be explained by π -Plasmon excitation [90, 91].

Figure 4-16 Schematic diagram of optical response of CNT exposed to beam along various propagation directions.

In order to fabricate CNT-based devices with an efficient light absorption or optical excitation of CNTs, Yamashita's group has proposed a method of direct synthesis of vertically-aligned CNTs (VACNTs) on quartz substrates [92]. However, the technique of free-space coupling is necessary in order to incorporate the quartz substrate into fiber laser cavity, which leads to increase the insertion loss and weaken the robustness of the whole laser system. Later, Song *et. al* have firstly demonstrated a CNT-based device with VACNT-film on a side-polished fiber for ultrafast pulse generation [81]. The VACNT-film was synthesized on a substrate and then transferred to a side-polished fiber using water as an inter-medium. Nevertheless, it is difficult to completely peel off the CNT-layer and the layer cannot stick firmly to an optical fiber. Therefore, one promising method to fabricate such CNT-based optical device could be the direct growth of VACNTs on waveguides using chemical vapor deposition (CVD) approaches [93]. Here, we experimentally demonstrate the direct growth of VACNTs with controllable tube diameter on a side-polished fiber by using various chemical vapor deposition (CVD) methods. The scanning electron microscopy (SEM) images and Raman spectrum are characterized confirming that VACNTs are successfully grown on optical fiber.

4.4.1 Plasma-enhanced CVD for Growth of Vertically-aligned CNTs on Fiber

The VACNTs used in the experiment are synthesized by the commercial Blackmagic system made by Aixtron (Germany). This system is capable of performing growth of VACNTs using thermal as well as plasma-enhanced CVD processes. Since plasma assists to dissociate gas at a relative low temperature, we start with plasma-enhanced

CVD (PECVD) method to investigate the possibility of direct growth of VACNTs on a side-polished fiber. In PECVD approach to growing VACNTs, CNTs are grown on the surface of a catalyst particle through the decomposition of carbonaceous gas and kept straightly in the presence of plasma when electrical field is applied [93]. As the nanotubes lengthen, their outermost walls interact with those of neighboring nanotubes via van der Waals forces to form a large bundle with sufficient rigidity. This rigidity enables nanotubes to keep growing along the original direction and form self-oriented array [94]. The procedure of VACNTs growth by PECVD involves four stages as shown in Fig. 4-17(a) [95]: (i) deposition of the catalyst layer onto targets; (ii) sintering the catalyst into island nano-particles generated by the surface tension from annealing; (iii) flowing of the carbonaceous decomposes to surface; and (iv) carbon diffusion through the catalyst particles under an activity gradient with carbon precipitates out on the opposite side.

Figure 4-17(a) Illustrations of growth of vertically-aligned carbon nanotubes (VACNTs) by chemical vapor deposition method; and (b) schematic diagram of VACNT on a side-polished fiber.

Fig. 4-17(b) shows the schematic diagram of a side-polished fiber where a VACNT-array is synthesized on the polished region of fiber. In our experiment, the side-polished fiber is prepared by a standard SMF with part of cladding removed in a length of 2 cm. Nickel is exploited as a catalyst to ensure VACNTs growth. Two gases Ammonia (NH_3) and Acetylene (C_2H_2) are adopted. The former one is used to etch by-products such as amorphous carbon and the latter one is used as a carbon feedstock gas. A thick layer of Nickel catalyst was deposited on polished-surface of fiber by electron beam (e-beam) deposition at room temperature. After the catalyst deposition, the side-polished fiber was transferred to a growth chamber which is then heated up to 800°C with an increment step of $100^\circ\text{C}/\text{min}$. The formation of islands of Nickel particles is conducted in NH_3 environment for 1 minute at 800°C . The growth of VACNTs on the fiber surface is carried out for duration of 10 minutes using C_2H_2 at 4:1 ratio, and the cathode voltage is biased at -800 V providing a plasma power of 100 W. The VACNTs are grown by the decomposition of the carbonaceous gas on the surface of the catalyst particles, where the carbon dissolves in the catalyst, diffuses through it, and exists to form the nanotubes.

The first challenge for VACNTs growth on a side-polished fiber is to ensure the reliability of underlying components in CVD chamber at a relatively high temperature. To cope with this challenge, we remove the coating of the whole fiber in order to avoid the burning of fiber coating which might contaminate the CVD chamber. Additionally, in order to fit in the size of the CVD chamber, a bare side-polished fiber has to be cut with a final length as short as 4 cm. Therefore, before the bare side-polished fiber is put into the CVD chamber, the two ends of fiber are well cleaved and the whole fiber is

packaged and fixed on a silicon wafer. The third challenge is to control the uniformity of VACNTs growth in terms of tube diameter, tube length, and density of the tubes on fiber surfaces. It is found that the thickness of the catalyst layer affects all those parameters. During the growth process, the thickness of catalyst layer is optimized to be 20 nm [95].

Figure 4-18 Scanning electron microscopy (SEM) images of VACNT-based fiber with the thickness of catalyst layer of (a) ~ 0 nm, (b) ~ 10 nm, and (c) ~ 20 nm.

The characterization of the finished fiber devices is carried out by measuring scanning electron microscope (SEM) images shown in Fig. 4-18. No CNT growth is observed with the absence of catalyst as shown in Fig. 4-18(a). VACNTs are not perfectly aligned and appear distorted when an initial catalyst layer of ~ 10 nm as shown in Fig. 4-18(b). VACNTs with relatively good morphology are observed when the thickness of catalyst layer of ~ 20 nm as shown in Fig. 4-18(c). The thickness of catalyst layer affects the morphology of VACNTs because the average island nano-particles size is dependent on the initial thickness of catalyst layer. In Fig. 4-18(c), the average length and diameter of VACNTs are $\sim 1 \mu\text{m}$ and ~ 100 nm, respectively. As the nanotube length is linearly proportional to growth time, the growth rate of tube length is estimated to be ~ 1.7 nm/s.

The variation of tube diameter is originated from non-uniform fragmentation of

catalyst particles. Although VACNTs might contain impurities which dilute the nanotube signature, structure information can still be extracted from its Raman spectrum. Fig. 4-19 shows the result of Raman spectroscopy of VACNTs grown on fiber when the catalyst thickness is optimized to be 20 nm. In the figure, two peaks falling in the range of 1370-1400 and 1580-1600 cm^{-1} refer to D-band and G-band, respectively. The former peak indicates the presence of defects while the latter one suggests the feature of graphite structure. The intensity of D peak and G peak in the spectrum are comparable due to plasma-induced defects, confirming the growth of VACNTs on silica surface [89].

Figure 4-19 Raman spectrum of fiber deposited with VACNTs by plasma-enhanced CVD.

4.4.2 Thermal CVD for Growth of Vertically-aligned CNTs on Fiber

For conventional CNT-based optical devices operating at 1550 nm, the tube diameter of CNTs has to be around 1 nm for a desirable optical absorption. Although plasma-enhanced CVD approach shows capability to directly grow VACNTs on optical fibers at a relatively low temperature, the plasma simultaneously etches VACNTs with smaller diameter during CVD process. In order to obtain VACNTs with smaller tube diameter,

we further conduct thermal CVD approach for the growth of VACNTs on side-polished fiber. The process involves two main stages: (i) formation of catalyst particles and (ii) growth of VACNTs on catalyst particles. In thermal CVD approach to growing VACNTs, CNTs are grown on the surface of a catalyst particle through the decomposition of carbonaceous gas and it is the Van Der Waals among nanotubes that forms the self-oriented large nanotube bundles with sufficient rigidity. In this approach, the major challenge is to balance the competing pathways leading to amorphous carbon formation rather than crystalline nanotube [96]. The common strategy is to add a vapor “etching” agent to the CVD atmosphere such as hydrogen. As a sequence, the tuning of tube diameter of VACNTs can be controlled by the timing and duration of hydrogen exposure in a fixed thermal process.

In the experiment, catalyst of Iron (Fe) is adopted to ensure a high density of individual CNTs. The sequence of gas for growing VACNTs is schematically illustrated in Fig. 4-20. Hydrogen (H_2) and C_2H_2 are used to etch by-products and provided as carbon feedstock gas, respectively. A 10-nm-thickness Alumina (Al_2O_3) as a barrier layer is deposited by e-beam evaporation followed by the coating of 2-nm-thickness Fe onto the polished-surface of fiber. The catalyst-deposited side-polished fiber is then put into the CVD chamber and heated up to 860 °C at a ramp rate of 200 °C/min. An annealing of 10 minutes is then carried out in a H_2 ambient to sinster the catalyst layer. C_2H_2 was then introduced for 5 minutes to perform the growth of VACNTs on the polished-surface of the fiber.

Figure 4-20 Gas-flowing sequence for growing VACNTs on optical fibers by thermal CVD method.

Fig. 4-21 shows the SEM images of VACNTs at the edge of side-polished fiber, demonstrating CNTs with around 10 μm in length in which the spatial uniformity are formed. The average diameter of individual VACNT is estimated to be around 8-10 nm and the average pitch between two tubes is about 20 nm. Since the diameter and areal density of the nanotubes array are correlated to the initial thickness of the catalyst layer in the CVD process, one can fabricate VACNT-based optical devices with the controllable tube diameter [96].

(a)

(b)

(c)

Figure 4-21 SEM images of fiber with the direct growth of VACNTs by thermal CVD: (a)-(c) VACNTs with different scales.

An additional insertion loss of 1.2 dB is measured for the VACNT-based side-polished fiber compared to a bare side-polished fiber. Since CNTs consist of shells of graphite which are birefringent, optical absorption of VACNTs film is believed to be polarization-sensitive depending on the alignment of each nanotube [97]. The

polarization dependent loss (PDL) of the prepared VACNT-based side-polished fiber is characterized by a system described in Ref. [98]. A tunable laser source with center wavelength of 1550 nm is applied to emit completely polarized light with stable polarization state. It is followed by a computer-controlled polarization controller and an in-line polarimeter (Thorlabs IPM 5300) to generate and monitor appropriate input Stokes parameters. Another polarimeter after the fiber under test is used to record the output Stokes parameters. By setting the input at four pre-determined polarization states, a 4×4 Muller matrix of fiber under test can be measured and PDL is derived from the Muller matrix [98]. By using this system, the PDL of VACNT-based side-polished fiber is calculated to be 0.5 dB.

4.5 Summary

This chapter mainly includes the fabrication of carbon-nanotube-based devices. Three methods are introduced including spray coating, optically-driven deposition, and chemical vapor deposition.

The spray method is relatively easy way to deposit CNTs on optical fibers for CNT-based devices. However, the manipulation of CNT particles in a small scale is difficult to be achieved since CNT solution is sprayed to targets in a large area. In addition, a large amount of CNTs is deposited outside the target that is wasted during the deposition process.

Optically-driven deposition has a number of advantages to fabricate CNT-based devices including the relatively controllable process in which CNTs are only deposited

onto the targeted area and the efficient in-use of CNTs. In order to construct fiber-end-type CNT-based devices, CNTs can be optically deposited on or around core region of fiber ends depending on the power level of incident light. In order to construct CNT-based devices with long-distance CNT-light interaction, we optically deposit CNTs along tapered fibers as well as side-polished fibers. By well designing the tapered fiber parameter and carefully controlling the CNT solution, we have made an improvement of CNT-deposited tapered fiber in terms of uniform distribution of CNT-layer in comparison to the peer reports. In addition, we have demonstrated CNT deposition on side-polished fiber for the first time.

Furthermore, we have demonstrated the possibility of direct growth of vertically-aligned CNT arrays on side-polished fibers by using plasma-enhanced CVD as well as thermal CVD methods. Plasma-enhanced CVD can ensure relatively straight CNTs on optical fiber, however, the tube diameter is large (around 100 nm) because the plasma simultaneously etches CNTs with smaller diameter during CVD process. In order to reduce the tube diameter, thermal CVD process is performed and the resultant VACNT has the tube diameter down to 8-10 nm.

Chapter 5 Enhancement of Thermal Damage Threshold of CNT-SAs

An important limitation in most of CNT-SAs is the relatively low thermal damage threshold. In order to solve this problem, the scheme of evanescent-field interaction with CNTs is proposed. There are two distinct formats demonstrated in this chapter: the long-length format and the thin-film format. Both formats can enhance the thermal damage threshold to some extent. The laser operations are included to study the performance of the prepared CNT-SAs.

5.1 Introduction

The conventional method to construct a CNT-SA can be simply a deposited CNT-layer or a CNT-polymer film sandwiched between fiber ferrule connectors or fiber ends [7, 17]. In such a way, the central part of optical field that carries the majority of power can effectively interact with the deposited CNTs. However, one concern of these schemes is the relatively low thermal damage threshold. Previous report shows that an optical power higher than 30 mW could damage CNTs by the generated heat [31]. In order to overcome the limitation, fiber-end-type CNT-SAs with various packaging have been reported whose major objective is achieving either the efficient heat-dissipation or the efficient heat-resistance including nanoporous-alumina-membrane-embedding [42], SiO₂-hosting [62], and siloxane-sealing [43]. As a result, the thermal damage threshold of CNT-SAs can be raised to 120 mW. Recently, a fiber-end-type CNT-SA sealed in

nitrogen environment has been demonstrated [44]. Since the oxidation is prevented by the surrounded nitrogen gas, such CNT-SA can operate at a high power level without deterioration. However, these methods incorporate extra materials as well as gas sealing which lose the basic simplicity advantage of CNT-SAs.

An alternative solution to tackle this problem is to utilize the interaction of evanescent-field of the propagating light with CNTs [32]. In optics, the evanescent field refers to the near-field wave with an exponential decay of the intensity as a function of the distance from the interface between two media. The physical explanation of the evanescent field is that the electric and magnetic fields cannot be discontinuous at the interface, which exhibits a penetration depth. One of the main applications of the evanescent field in optical fiber nowadays is optical sensing [99]. Indeed, the evanescent-field interaction can be explored to enhance the thermal damage threshold of CNT-SAs since only a part of light heats on the deposited CNTs. According to the interaction distance, CNT-SAs can be classified into two formats: the long-distance format and the thin-film format. The interaction between the evanescent-field and CNTs in long-distance format can be achieved by the deposition of CNT-layer along the specialty fibers. The most used fibers are tapered fibers and side-polished fibers, in which the propagation mode broadens into surroundings due to the modification of fiber structures. In addition to the enhancement of thermal damage threshold, the CNT-deposited specialty fibers can achieve the functional nonlinear devices by controlling the interaction length [76, 77]. However, such schemes with the modification of the fiber structures can generate extra polarization sensitivity and scattering loss, which in turn limits its applications.

In order to overcome above limitations, we propose a CNT-SA with ring pattern of CNTs on end-facet of standard SMF for the first time, in which the interaction between CNTs and the evanescent field in an optical fiber takes place in a thin-film format. The advantages of such scheme of CNT-SAs include the relatively high thermal damage threshold, the compact device with low loss, polarization-insensitive, and easy fabrication without the modification of fiber structure. Furthermore, an all-fiber Fabry-Perot (FP) linear cavity laser is constructed incorporating the prepared CNT-SA, where the optical power is confined in a relatively short laser cavity to investigate the thermal damage threshold and the performance of the CNT-SA. Together with the proper design of cavity configuration, the lasers can operate in the Q-switching state for high-energy pulse generation as well as in the mode-locking state for ultrashort pulse generation. The experimental results show that the prepared CNT-SAs with evanescent-field interaction in a thin-film format can withstand a relatively high power without performance degradation.

5.2 Evanescent-field Interaction with CNTs in a Long-distance Format

As discussed previously, the key technique to enhance thermal damage threshold of CNT-SAs is to explore the scheme of CNT-evanescent-field interaction. In this section, we focus on the investigation of CNT-SAs with CNT-evanescent-field interaction along a side-polished fiber. On one hand, such a CNT-SA with CNT deposition on side-polished fiber is related to a CNT-SA with CNT deposition on fiber end in ring pattern, because the two types of CNT-SAs are both based on mechanism of CNT-evanescent-

field interaction for enhancing the thermal damage threshold. On the other hand, a CNT-SA with CNT deposition on side-polished fiber is different from a CNT-SA with CNT deposition on fiber with ring pattern, because the former is to control the interaction distance while the latter is to manage the interaction area. Since there exists the similarities and differences between the two types of CNT-SAs, before we introduce the fiber-end-type CNT-SA with ring pattern, it is interesting to study how CNT-deposited side-polished fiber influences the laser performance.

For the first time to our knowledge, we demonstrate that a CNT-deposited side-polished fiber with high thermal damage threshold of ~58 mW can assist fiber laser to produce Q-switched pulses with pulse energy of ~81.3 nJ which is higher than current reports using CNT-SAs. However, such an asymmetrical CNT-based fiber device can inevitably cause some polarization dependent losses which leads to polarization-sensitivity and artificial birefringent filtering, and therefore the fiber laser towards mode-locking state can produce multiple types of pulse.

5.2.1 Laser Application

As mentioned in Chapter 2, CNT-SAs can assist a laser system to generate stable pulse trains. Together with a proper design of cavity configuration, CNT-SAs can be used to enable laser systems to operate in either Q-switching or mode-locking regime with different features [21, 80, 100-102]. Q-switched fiber lasers have advantages over mode-locked fiber lasers in high energy pulse generation [103], while the mode-locked lasers can generate ultrashort pulses ranging from picosecond to sub-picosecond [104]. In this section, we demonstrate that benefiting from the scheme of CNT-

evanescent-field interaction along a side-polished fiber, pulses with pulse energy as high as 81.3 nJ can be achieved from Q-switched fiber lasers.

5.2.1.1 Q-switching Operation

Figure 5-1 Experimental setup for passively Q-switched fiber laser incorporating CNT-deposited side-polished fiber: erbium-doped fiber (EDF); wavelength-division multiplexing (WDM); polarization controller (PC).

Fig. 5-1 shows the experimental setup of the passively Q-switched fiber laser with ring-configuration. A 976 nm laser diode is used to pump a 0.6-m-long erbium-doped fiber (EDF: LIKKIE 110) through a 980/1550 nm wavelength-division multiplexing (WDM) coupler. An optical isolator is applied to ensure unidirectional operation of light in the cavity. A fiber-based PC is incorporated in the laser cavity for optimization of the laser operation. 10% of the optical power is extracted from the cavity as the laser output by a 90/10 coupler. The applied CNT-deposited side-polished fiber is prepared by optically-driven deposition method and its microscopic image is given in Fig. 4-16(c). The length of deposited CNT-layer on the fiber is estimated to be 390 μm . As only a portion of evanescent wave in side-polished fiber interacts with CNTs, it is difficult to

characterize the nonlinear absorption of CNT-deposited side-polished fiber by using our pulsed light source with a limited average power of 20 mW. We can characterize the total insertion loss of CNT-deposited side-polished fiber at C-band which is about ~1.4 dB. The CNT-deposited side-polished fiber is directly spliced into the laser cavity. Spectral and temporal profiles of the laser output are characterized by an optical spectrum analyzer (OSA: AQ6317B) with a resolution of 0.01 nm and a 1.2-GHz photodetector (DET01CFC) followed by a 350-MHz oscilloscope (Agilent 54641A), respectively.

Figure 5-2 Output from the Q-switched fiber laser incorporating CNT-deposited side-polished fiber: (a) optical spectrum; (b) optical pulse train; (c) pulse duration and (d) pulse energy against pump power.

The generation of pulses in Q-switching regime starts under an input pump power of 132.3 mW. The 3-dB bandwidth of spectrum is measured to be 0.12 nm at the center wavelength of 1563.1 nm as shown in Fig. 5-2(a). An average output power of 3.2 mW is measured. There is no chirp appeared on the optical spectrum near the center wavelength, indicating that the cavity perturbation is suppressed [100]. Fig. 5-2(b) depicts the output pulse train with repetition rate and pulse width of 56.2 kHz and 6.6 μ s, respectively. There is no amplitude modulation shown on the pulse envelope, illustrating that the effect of self-mode-locking on Q-switching operation is suppressed. As a comparison, the same experiment is repeated by embedding a bare side-polished fiber into the cavity and no pulse generation is observed. It confirms that the generation of pulses originates from the CNT-based fiber device in the cavity and not the fiber itself. For conventional ring cavity fiber lasers that operate in Q-switching and prohibit from broadband mode-locking, the cavity configurations need SAs as well as narrowband filters such as fiber Bragg grating which could sacrifice the intra-cavity energy [80, 100]. In this experiment, a passively Q-switched ring cavity fiber laser with a CNT- SA having no lasing mode selector, and Q-switching is generated in a ring cavity without the transient of mode-locking and Q-switched mode-locking.

By increasing the pump power from 132.3 mW to 209.6 mW, stable pulses are obtained from the laser cavity. The pulse width varies from 6.6 to 4.5 μ s, while the average output power monotonically increases as plotted in Fig. 5-2(c). The repetition rate is also detuned from 56.2 kHz to 70.4 kHz, further confirming the constructed laser is working in passively Q-switching regime. The pulse energy increases as the pump power increases as shown in Fig. 5-2(d). Benefiting from the scheme of CNT-

evanescent-field interaction, pulse energy as high as 81.3 nJ is achieved under a pump power of 209.6 mW with an intra-cavity power of 58 mW. The obtained pulse energy in the experiment is found to be higher than previous reports using CNT-SAs [80, 100-102]. Although such pulse energy is still cannot outperform that using convention semiconductor-based saturable absorber [105, 106], further improvement for scaling up pulse energy is foreseeable with CNT-SA via evanescent-field interaction for high damage threshold together with optimizing the cavity length and cavity loss. The experimental results demonstrate that the CNT-deposited side-polished fiber can work without significant degradation at an intra-cavity power level of ~58 mW.

5.2.1.2 Mode-locking Operation

Fig. 5-3 shows the experimental setup of the mode-locked fiber laser incorporating the CNT-deposited side-polished fiber. The net cavity dispersion of the laser is managed for mode-locking operation. A 976 nm laser diode is used to backward pump a 0.6-m-long EDF (LIEKKI Er110) with a group velocity dispersion (GVD) parameter β_2 of +0.012 ps²/m through a 980/1550 nm WDM coupler. The pigtailed fiber of the WDM coupler comes with a 0.35-m-long HI1060 fiber with a β_2 of +0.02 ps²/m. The rest cavity fibers are standard SMFs. The total cavity length is about 13.2 m, and the net cavity dispersion is around -0.255 ps². An optical isolator is applied to ensure unidirectional operation of light in the laser cavity. A fiber-based PC is used to adjust and optimize linear birefringence of the laser cavity. 10% of the optical power is extracted from the cavity as an output through a 90/10 coupler. The applied CNT-deposited side-polished fiber is

prepared by optically-driven deposition method and its microscopic image is given in Fig. 4-16(b). Such CNT-deposited side-polished fiber has an insertion loss of ~ 1.2 dB.

Figure 5-3 Experimental setup for passively mode-locked fiber laser incorporating CNT-deposited side-polished fiber.

The self-started mode-locking of the constructed laser is easily achieved under a pump power of 38.9 mW. The corresponding average output power is measured to be 0.858 mW. Fig. 5-4(a) shows that bright pulses are circulating in the cavity with a round-trip time of 64.1 ns which is corresponding to the cavity fundamental frequency of 15.6 MHz. Fig. 5-4(d) gives the output optical spectrum (the light gray curve), in which the center-wavelength is located at 1565.58 nm with a 3-dB bandwidth of 0.2 nm. By keeping the operation conditions except for increasing the pump power up to 50.6 mW, dark pulses are circulating in the cavity repeated at 15.6 MHz as shown in Fig. 5-4(b). An additional wavelength appears on spectrum (the black curve) as shown in Fig. 5-4(d). Although no obvious polarizer is incorporated in the cavity, the slightly residual polarization asymmetry of the used components such as the side-polished fiber, can

cause the formation of a linear artificial birefringent filter. The existence of the artificial birefringent filter leads to the multi-wavelength emission within the effective laser gain bandwidth. The strong cross-phase coupling between the dual-wavelength could form the domain wall dark solitons [107, 108].

Figure 5-4 Output from the mode-locked fiber laser incorporating CNT-deposited side-polished fiber: (a) bright pulse; (b) dark pulse; (c) transformation from bright to dark pulse; and (d) optical spectra ($p_1=38.9$ mW, $p_2=42.7$ mW, and $p_3=50.6$ mW).

Comparative experiments are performed, in which we replace the CNT-deposited side-polished fiber by a SMF as well as a bare side-polished fiber under the optimized

polarization states. Even though the pump power is pushed up to 200 mW, only continuous wave emission is obtained. It indicates that bright and dark pulses are formed with the help from the CNT-deposited side-polished fiber. Since CNTs exhibit strong third-order susceptibility, Kerr nonlinearity of a laser cavity can be enhanced by CNT-deposited side-polished fibers [75, 76]. Fig. 5-4(c) shows the pump-induced transformation of single bright pulse into dark pulse from the developed fiber laser within a cavity round-trip time. The middle state emitting bright-dark pulse is recorded under a pump power of 42.7 mW whose optical spectrum (the gray curve) is shown in Fig. 5-4(d). The obtained results demonstrate that the CNT-deposited side-polished fibers can assist the fiber laser to produce multiple types of pulses.

5.2.2 Results Discussion

In this section, we have investigated the scheme of evanescent-field interaction with CNTs in a long-distant format to enhance the thermal damage threshold of CNT-SAs. The CNT deposition on side-polished fibers is mainly studied. The experimental results show that the prepared CNT-deposited side-polished fiber can improve the thermal damage threshold of CNT-SAs up to ~58 mW that is almost twice times the thermal damage threshold of the conventional CNT-SAs. Such CNT-based side-polished fiber can assist the constructed fiber laser to produce high-energy pulses of ~81.3 nJ in the Q-switching regime and multiple types of pulses in the mode-locking regime. However, CNT-deposited side-polished fibers are found sensitive to polarization variation due to asymmetric geometry of fiber structure. Fig. 5-5 shows a comparison of a bare side-polished fibers and a CNT-deposited side-polished fiber having different polarization

dependent loss (PDL). The PDL increases when CNTs are coated on the side-polished fiber. Such polarization-dependent feature of the CNT-based fiber device could enable the mode-locked fiber lasers to operate in the multiple states [109, 110]. On the other hand, it tends to cause the instability of laser operation originated from the change of environmental temperature and the vibration of polarization state. To mitigate the polarization sensitivity of CNT-SAs, a new scheme of evanescent-field interaction with CNTs is necessary.

Figure 5-5 Polarization dependent loss of side-polished fiber before and after CNT deposition.

5.3 Evanescent-field Interaction with CNTs in a Thin-film Format

Fig. 5-6 shows the schematic diagram of evanescent-field interaction with CNTs in a thin-film format. The CNT-layer with a ring pattern is proposed to construct a fiber-end-type CNT-SA. Since only a portion of light interacts with CNTs, the optical absorption induced heating can be greatly reduced which results in the relatively high thermal

damage threshold of the whole device. As the optical field is mainly confined in the core region of the fiber, it is expected that the CNT-SA with a larger inner ring diameter can have higher thermal damage threshold, which exhibits lower optical absorption in comparison to one with a smaller inner ring diameter.

Figure 5-6 Schematic diagram of evanescent-field interaction with CNTs deposited on fiber end.

Figure 5-7 Calculated field distribution of the fundamental mode in standard SMF.

Fig. 5-7 depicts the field distribution of the fundamental mode in a standard SMF, which is solved by Eigen-equations described in section 3.2.1.4. It is calculated that around 50% of the optical power is distributed beyond a diameter of 6.5 μm while less than 1% of optical power is distributed exceeding a diameter of 22 μm . In order to achieve an efficient evanescent-field interaction as well as minimize the optical absorption-induced heating, the inner ring diameter of CNTs on the fiber connector end is optimized between 9-15 μm . The fabrication of the CNT-SAs is done by optically-driven deposition method as described in Chapter 4. Next, the optical absorption as well as the thermal damage threshold of the CNT-deposited fiber ends with various inner ring diameters is characterized.

5.3.1 Optical Characterization

The nonlinear transmission property of the prepared CNT-SA with an inner ring diameter of ~ 10 μm is characterized by a 1.55- μm mode-locked fiber laser. The laser delivers a pulse train with a pulse width of 260 fs, a repetition rate of 68.27 MHz, and an average power of 20 mW. Before the pulse train is launched into the CNT-SA, a tunable attenuator is adopted to adjust the input average power. Fig. 5-8 shows that the optical absorption of the CNT-SA with the inner ring diameter of ~ 10 μm , which exhibits a trend of saturation with an increasing of input power. The saturable absorption and non-saturable loss are estimated to be 2.6% and 16.3%, respectively. The saturable absorption in the different polarization state of the incident light is believed to be minimal due to the small PDL of the device. Since the effective mode area of the standard SMF is around 100 μm^2 , the saturation fluence of the CNT-SA, defined as the

saturation energy per unit area, is estimated to be $47.2 \mu\text{J}/\text{cm}^2$. As a comparison, we prepare a CNT-SA that CNTs are directly sprayed onto the connector end and evenly covering the entire core region. It bears a similar insertion loss with the proposed CNT-SA while exhibits a lower saturation fluence of $\sim 22.4 \mu\text{J}/\text{cm}^2$. The relatively high saturation fluence in the CNT-SA with a ring pattern is a result of the efficient evanescent-field interaction as only a portion of light interacts with CNTs. It is worth mentioning that the measured PDL of the prepared CNT-SA is as small as $\sim 0.05 \text{ dB}$ at $1.55 \mu\text{m}$. Since evanescent-field interaction only occurs through a thin-film CNTs, the accumulation of polarization-dependent absorption by the CNTs in the proposed device is smaller in comparison to the one with evanescent-field interaction over a longer interaction length [32, 40].

Figure 5-8 Saturable absorption of CNTs deposited on fiber end with an inner ring diameter of $10 \mu\text{m}$.

The nonlinear transmissions of CNT-SAs with various inner ring diameters are also characterized. Fig. 5-9 plots the modulation depth and the non-saturable loss of the CNT-SAs in the relationship of the inner ring diameter. It shows that the modulation depth and the nonsaturable loss are inversely proportional to the inner ring diameter.

Figure 5-9 The modulation depth and the non-saturable loss of CNT-SAs against inner ring diameter.

In order to study the long-term reliability of the CNT-SAs which are exposed to high incident power, we characterize the real-time power-dependent transmission of the CNT-SAs with an inner ring diameter of $\sim 10 \mu\text{m}$ for hours. Although the roles of the peak power and the average power in the damage thresholds of CNT-SAs are yet confirmed, it has been reported that for pulsed and CW laser operation the damage of CNT-SAs takes place at similar power levels [44]. We use a CW $1.55\text{-}\mu\text{m}$ LD as the light source followed by a variable-gain EDFA. The CNT-SAs with and without ring pattern are characterized for comparison.

Figure 5-10 Real-time power-dependent transmission of CNT-SA with CNTs deposited on core region.

Figure 5-11 Real-time power-dependent transmission of CNT-SA with an inner ring diameter of $\sim 10 \mu\text{m}$.

Fig. 5-10 shows the normalized-transmission of the CNT-SA with CNTs evenly covering the core region at different incident power levels. From the results, it is clearly observed that the transmission starts to decrease after the laser is switched on under an

incident power of 30 mW. Such decrease rate of the transmission can be used to describe the performance of CNT-SAs over time. It is estimated to be 14% per hour for the CNT-SA without ring pattern from the results. Since the high incident power could induce graphitization and structure variation of CNTs, the optical induced heating over the threshold power causes damage to the CNT-film and increases the absorption of CNT-based devices [31]. On the other hand, the CNT-SA with a ring pattern exhibits much less increase in absorption with an input power of ~70 mW for more than 5 hours as shown in Fig. 5-11. The decrease rate of the transmission is estimated to be less than 0.04% per hour. The results suggest that the thermal damage threshold of such a CNT-SA is increased by around 130% compared with the evenly deposited one.

Table 5-1 Characteristics of CNT-SAs with various ring diameters.

Ring Diameter (μm)	Saturation Fluence ($\mu\text{J}/\text{cm}^2$)	Modulation Depth (%)	Non-saturable Loss (%)	Thermal Damage Threshold (mW)
0	22.4	12.5	47	~30
4	30.5	6.4	34.7	~40
10	47.2	2.6	16.3	~70
14	>75.96	<1	<10	~126

As stated in section 2.1.2, important parameters of CNT-SAs for laser mode locking include recovery time, saturation fluence, modulation depth, non-saturable loss, and thermal damage threshold. The recovery time should be fast as long as CNTs are used, but the other parameters are dependent on device structures. Table 5-1 summarizes the performance indexes of CNT-SAs with various inner ring diameters. By increasing the inner ring diameter, the thermal damage threshold of CNT-SAs is enhanced gradually.

With the ring diameter of $\sim 14\ \mu\text{m}$, the thermal damage threshold can be raised up to $\sim 126\ \text{mw}$, which is higher than the current reports about thermal damage threshold of thin-film CNT-SA [31, 43, 62]. However, the modulation depth of CNT-SAs decreases when the inner ring diameter increases. In order to achieve a desirable saturable absorption as well as a high thermal damaged threshold for pulsed laser applications, a CNT-SA with an appropriate ring diameter should be selected.

5.3.2 Laser Application

5.3.2.1 Q-switching Operation

Fig. 5-12 shows the experimental setup of a Q-switched fiber laser with linear Fabry–Pérot cavity. In order to reduce the intra-cavity loss for high-energy pulse generation, the pump source consisting of a 976-nm LD and a 980/1550-nm WDM coupler is located outside the master oscillator. A dielectric mirror (mirror-1) is included to couple the pump into the laser cavity and extract 10% of the power at the emission wavelength from the laser cavity. Mirror-2 with a high reflection of around $\sim 99\%$ provides the other side of cavity feedback. A 0.3-m-long EDF (LIKKIE 80) is employed as the gain medium. An isolator located at the output port blocks the deleterious reflection from the end-facet of the port. In order to achieve a high-energy Q-switched fiber laser, the low cavity loss is necessary. The CNT-deposited fiber end with an inner ring diameter of $\sim 14\ \mu\text{m}$ is selected in the experiment. The CNT-SA is constructed by connecting the prepared CNT-deposited fiber end to a clean fiber end through an optical fiber holder filling with the refractive index matching oil.

Figure 5-12 Experimental setup for passively Q-switched fiber laser incorporating CNT-deposited fiber end with ring pattern.

Comparative experiments on the fiber laser are firstly studied where a clean fiber end is incorporated instead of a CNT-deposited fiber end. No pulse emission is observed even if the pump power is at its maximum value around 264.3 mW. Then the prepared CNT-deposited fiber end is included. By tuning the pump power, stable Q-switched pulse trains are obtained as shown in Fig. 5-13(a). Unlike passively mode-locking where the repetition rate of output pulse train is fixed, the repetition rate of Q-switched fiber laser can be tuned which is mainly relying on the lifetime of gain medium. When more gain is provided to saturate a SA, pulse energy is growing monotonically with the increase of the pump power.

When pump power is increased from 14.4 to 264.3 mW, the output average power and pulse energy of the laser can be tuned in a range of 0.06-12.6 mW and 6.8-114 nJ, respectively, as shown in Fig. 5-13(b). It is noted that the obtained pulse energy in the experiment is found to be higher than previous reports using CNT-SAs [80, 100-102]. Even though the pump power is at high power level, the laser constantly operates in Q-switching state instead of mode-locking state. This happens because the incorporated CNT-SA with a small gap between the two fiber-ends can act as an effective FP filter to suppress the broadband mode-locking. The constructed Q-switched fiber laser is tested

under pump power of 264.3 mW with the intra-cavity power of 126 mW for more than 1 hour. The output pulses are well stabilized both in time domain as well as frequency domain as shown in Figs. 5-13(c) and (d), indicating the CNT-deposited fiber end with a ring pattern can work well at such a high power without degradation.

Figure 5-13 Output from the Q-switched fiber laser incorporating a CNT-deposited fiber end with ring pattern: (a) optical pulse train; (b) average power and pulse energy under various pump powers. Stability of the laser: (c) repetition rate and pulse duration; (d) optical spectra (curves 1, 2 and 3 refer to the laser recorded at 0, 30 and 70 minutes).

5.3.2.2 Mode-locking Operation

A 1.55- μm FP linear-cavity passively mode-locked fiber laser is further constructed to investigate the performance of the fabricated CNT-SA. In general, the fundamental repetition rate of the mode-locked laser is determined by:

$$f_{rep} = c/2nL \quad (5-1)$$

where c is the velocity of light in vacuum, L is the cavity length, and n is the refractive index of the fiber core. Compared with the ring-configuration mode-locked fiber lasers, a linear-configuration FP mode-locked laser can achieve a shorter cavity length thus a higher repetition rate [111, 112]. It is reported that such short cavity laser tends to encounter an issue that the laser is significantly heated up during operation [112]. The mode-locking operation could be failed by any of the cavity components that cannot endure the generated heat. Therefore, the thermal damage threshold of SA becomes crucial.

Fig. 5-14 shows the experimental setup of the FP linear-cavity passively mode-locked fiber laser incorporating the proposed fiber-end-type CNT-SA. In order to remove the effective FP filter inside the master oscillator, the CNT-deposited fiber end with an inner ring diameter of $\sim 10 \mu\text{m}$ is directly mated to a highly reflective mirror (mirror-2) to serve as a reflective SA. To shorten the cavity length for a high repetition rate, a 0.16-m-long EDF (LIEKKI Er80) with β_2 of $-0.022 \text{ ps}^2/\text{m}$ is used as the gain medium. A fiber-based PC is incorporated to match the roundtrip state of polarization. Other components are the similar to the ones as shown in Fig. 5-12. The total length of the fiber inside the master oscillator is $\sim 0.49 \text{ m}$ and the net β_2 is managed to be -0.022 ps^2 for soliton

shaping. The RF spectrum of the output pulse train is measured by a signal source analyzer (Rohde & Schwarz) and the autocorrelation of pulse train is taken by an autocorrelator (Alnair Labs HAC-200).

Figure 5-14 Experimental setup for passively mode-locked fiber laser incorporating CNT-deposited fiber end with ring pattern.

In the experiment, the pump power threshold of single-soliton generation is found to be 96 mW. To achieve single soliton with a relatively high output power, the pump power is fixed at 150 mW. Fig. 5-15(a) shows the corresponding optical output spectrum. The center wavelength is 1563.3 nm and the 3-dB bandwidth is estimated to be 4.4 nm. The output pulse train is given in the inset of Fig. 5-15(b), exhibiting little change on the envelope. The autocorrelation trace of the output pulse is measured to be around 680 fs with a sech^2 -pulse shape fitting as shown in Fig. 5-15(c). The calculated time-bandwidth product is 0.368, indicating that the optical pulse is nearly transformed-limited. Fig. 5-15(d) shows the RF spectrum of the pulse train with a fundamental repetition rate of 211.84 MHz corresponding to the cavity length. The RF spectrum with a frequency span of 500 kHz and a resolution of 200 Hz shows an extinction ratio of 83 dB at the fundamental frequency, indicating that a stable mode-locking is obtained. The inset of Fig. 4-15(d) further depicts the wideband RF spectrum up to 3 GHz. There is no

sideband among the harmonic frequencies, which further confirms the stable mode-locking operation.

Figure 5-15 Output from the mode-locked fiber laser incorporating the CNT-deposited fiber end with ring pattern: (a) optical spectrum; (b) pulse train; (c) autocorrelation trace, and (d) the corresponding RF spectrum (the inset shows a wide frequency-range).

When the pump power exceeds 160 mW towards maximum value of 240 mW, multiple pulses are generated within one round-trip due to the soliton energy quantization [113]. The optical power versus pump power is shown in Fig. 5-16(a). When the pump power is pushed up to 240 mW, the intra-cavity average power of the constructed FP mode-locked laser is higher than 30 mW. The long-term stability of the

developed FP mode-locked fiber laser with an intra-cavity power higher than 30 mW is investigated for a 12-hour continuous operation. The output of the mode-locked fiber laser shows no degradation in both optical spectrum and RF spectrum. It demonstrates that the proposed CNT-SA can withstand a relatively high optical power without significant performance degradation. Previous report shows that the FP mode-locked fiber laser with high repetition rate is built with a CNT-film attached to the end-facet of a special gain fiber with a core diameter of 14 μm [52]. Owing to the relatively large mode field diameter of the fiber, the CNT-SA can sustain a relatively high intra-cavity power. It is worth noting that CNTs are deposited on the end-facet of a ferrule connector with standard SMF in our work.

By carefully adjusting polarization controller, bound states of soliton appear. Fig 5-16(b) shows one of states of bound solitons under a pump power of 240 mW. The optical spectrum of bound solitons is strongly modulated due to that two solitons are closely spaced in the time domain. The free space range (FSR) or period of the spectral modulation is ~ 2.4 nm, and according to the Fourier transformation it corresponds to a soliton separation of ~ 3.6 ps in the time domain. A spectral dip at the center of the spectrum indicates that the phase difference between bound solitons is π [60]. The inset of Fig. 5-16(b) plots the corresponding autocorrelation trace. Three peaks with an intensity ratio of 1:2:1 in the autocorrelation trace reveal that two pulses with identical intensity and duration propagate close to each other in time domain. The autocorrelation trace also shows that the pulse separation is in agreement with the spectral modulation period. By changing orientations of PC, the bound state of solitons with different separation is shown in Fig. 5-16(c). The FSR of spectrum is ~ 3.4 nm and the

corresponding autocorrelation trace has a pulse separation of ~ 2.5 ps as shown in the inset of Fig. 5-16(c). Fig. 5-16(d) plots various sets of bound states of soliton obtained in the experiment, in which the relationship between pulse separation and FSR follows Fourier transformation algorithm. Benefiting from the evanescent-field interaction in the proposed CNT-SA that enables mode-locked laser to operate at the relatively high intra-cavity power, we have demonstrated bound states of soliton with a high fundamental repetition rate from CNT-based mode-locked fiber laser for the first time.

Figure 5-16 Output from the mode-locked fiber laser incorporating the CNT-deposited fiber end with ring pattern: (a) output power; (b)-(c) optical spectra of bound states of soliton-like pulses showing together autocorrelation traces; and (d) pulse separation in the relationship of spectral FSR.

5.3.3 Results Discussion

In the section, we have demonstrated a scheme of evanescent-field interaction with CNTs in a thin-film format to enhance the thermal damage threshold of CNT-SAs. The CNT-layer is deposited on fiber end in a ring pattern for evanescent-field interaction rather than direct interaction.

On one hand, the advantages of such fiber-end-type CNT-SAs are noteworthy including: (i) relatively high thermal damage threshold; (ii) simple device without the modification of fiber structure as well as the incorporation of extra material; (iii) environmental robustness with highly compatible to the fiber and polarization insensitive; and (iv) small-print for the short-cavity laser applications. For different inner ring diameter of CNT-layer, the proposed CNT-SAs can endure various power levels of incident light. Experimental results demonstrate that fabricated CNT-SAs with the inner ring diameters of 0 μm , 10 μm and 14 μm can endure the incident power of 30 mW, 70 mW, and 126 mW, respectively. Furthermore, such CNT-SAs with desirable inner ring diameters can assist the fiber laser to produce pulses with energy as high as ~ 114 nJ in the Q-switching regime, and pulses with short pulse width of ~ 680 fs and high repetition rate of ~ 211.84 MHz in the mode-locking regime.

However, the fiber-end-type CNT-SA with ring pattern has a trade-off between thermal damage threshold and modulation depth as shown in Table 5-1. For higher thermal damage threshold, the ring diameter of CNT-SA should be larger which results in the reduction of its overall loss. However, it also reduces the nonlinear absorption of CNT-SAs that is desirable for pulse-reshaping in fiber lasers. Based on above facts, the

proposed CNT-SAs provide great merits in the applications where mode-locked fiber lasers require SAs with high thermal damage threshold. However, for mode-locked fiber lasers that require large nonlinear absorption, the proposed CNT-SAs with ring pattern are not applicable. In order to determine how much of the nonlinear absorption (or modulation depth) of CNT-SA is desirable in practical applications, we have conducted the optimization of modulation depth of CNT-SAs in the following chapter.

5.4 Summary

In this chapter, we mainly focus on the enhancement of thermal damage threshold of CNT-SAs. The working mechanism of the proposed CNT-SAs is based on evanescent-field interaction with CNTs. Depending on the interaction distant, two formats are involved: the long-distance format and the thin-film format. Regarding the evanescent-field interaction with CNTs in a long-distance format, we have investigated the performance of CNT-deposited side-polished fibers in laser applications. The experimental results show that the CNT-deposited side-polished fiber can expose to an incident power of ~58 mW without performance degradation. On the other hand, the prepared CNT-deposited side-polished fiber fiber is sensitive to polarization change due to the asymmetric geometry of fiber structure. Such CNT-deposited side-polished fiber can assist the constructed fiber laser to produce high-energy pulses of ~81.3 nJ in the Q-switching regime and multiple types of pulses in the mode-locking regime.

In order to achieve a robust and compact CNT-SA with an enhanced thermal damage threshold, we propose and demonstrate a CNT-SA with the evanescent-field interaction

in a thin-film format. CNTs are deposited onto the end-facet of SMF in a ring pattern. The thermal damage threshold of the CNT-SA with an inner ring diameter of $\sim 10\text{ }\mu\text{m}$ is improved by $\sim 130\%$ compared to the one without ring pattern. The CNT-SA with ring pattern is further incorporated into an all-fiber FP cavity for pulse generation. The results demonstrate that the CNT-SA with ring pattern can assist the constructed fiber laser to produce pulses with pulse energy as high as $\sim 114\text{ nJ}$ in the Q-switching regime, and pulses with short pulse width of $\sim 680\text{ fs}$ and high repetition rate of $\sim 211.84\text{ MHz}$ in the mode-locking regime. Furthermore, benefiting from the evanescent-field interaction in the proposed CNT that enables mode-locked laser to operate at the relatively high intra-cavity power, we have demonstrated bound states of soliton with a high fundamental repetition rate from CNT-based mode-locked fiber laser for the first time.

Chapter 6 Optimization of Modulation Depth of CNT-SAs for Dispersion-managed Mode-Locked Fiber Lasers

This chapter systemically investigates the optimization of modulation depth of saturable absorbers in the stabilization of dispersion-managed mode-locked fiber lasers with net cavity dispersion near zero. The simulation results are consistent with experimental observations.

6.1 Introduction

Passively mode-locked fiber lasers have emerged as one of the best pulsed light sources for a broad range of applications, such as optical communication, frequency metrology, microscopy, and micromachining [1]. One of the great merits of passively mode-locked fiber lasers is the restively flexible management of net cavity dispersion ($\beta_{net}^{(2)}$) which enables the lasers to produce stretched-pulses with excellent performance [114-118]. In 1995, theoretical studies have shown that pulses with the shortest pulse width and the largest spectral bandwidth could be generated from the dispersion-managed mode-locked fiber laser with $\beta_{net}^{(2)}$ close to zero [49, 119]. Experimentally, pulses with the pulse width of ~37.4 fs and the spectral bandwidth of ~135 nm are generated from the laser with $\beta_{net}^{(2)}$ of -0.002 ps² [119]. Such lasers are generally exploring nonlinear polarization rotation (NPR) technique as the artificial saturable absorber in which the modulation depth is adjustable with the polarization controller. Nevertheless, one issue of NPR technique is that the optimum polarization settings can

drift with temperature and it is difficult to experimentally qualify and reproduce the achieved modulation depth. In order to improve the mode-locked fiber lasers with more robust and compact cavities, semiconductor SAs have been extensively explored [5, 120-122]. Recently, it has shown that a dispersion-managed mode-locked fiber laser incorporating CNT-SAs can generate pulses with the pulse width of ~ 74 fs and the spectral bandwidth of ~ 63 nm when $\beta_{net}^{(2)}$ is -0.003 ps^2 [50]. However, the major limitation of the dispersion-managed mode-locked fiber lasers with $\beta_{net}^{(2)}$ near zero is that the laser tends to produce an unstable pulse burst instead of a stably mode-locked pulse train [56, 123, 124]. Previous report attempts to explain the phenomena of the unstable operation of the laser by considering the strong gain filtering effect [123]. To compensate for the loss induced by spectral filtering, the related reports mention that a SA with a larger modulation depth is necessary for the stable mode-locking operation [72, 120]. However, it is not yet experimentally and numerically confirmed that how much of $\beta_{net}^{(2)}$ can be pushed toward zero for the laser to operate in the stable mode-locking state by a SA with a larger modulation depth.

In this Chapter, we experimentally investigate CNT-SAs with different modulation depths on stabilizing the mode-locking operation in dispersion-managed fiber lasers with $\beta_{net}^{(2)}$ close to zero. It is found that the unstable region of the laser could be shrunk by $\sim 31.3\%$ when modulation depth of SA is increased from 6.4% to 12.5%. The numerical analysis is also performed to investigate the dispersion-managed mode-locked fiber laser with different modulation depth of SAs, which is consistent with the experimental observation. The obtained results are not merely applicable to the fiber lasers

incorporating CNT-SAs, but also could be a general guidance for the design of the dispersion-managed mode-locked fiber lasers using similar kinds of SAs.

6.2 Experiments on CNT-SAs Incorporated Dispersion-Managed Mode-locked Fiber Lasers

Figure 6-1 Experimental setup for dispersion-managed mode-locked fiber lasers incorporating CNT-SAs.

In order to confirm that laser instability is the general feature of most dispersion-managed fiber lasers when the net cavity dispersion approaches zero, we have developed a dispersion-managed fiber laser which is similar to other reported works. The experimental setup of the dispersion-managed mode-locked fiber laser incorporating CNT-SAs is shown in Fig. 6-1. A 7.32-m-long EDF (EDF-980-T1) with the group velocity dispersion parameter ($\beta^{(2)}$) of $+23.4 \text{ ps}^2/\text{km}$ is pumped by a 976-nm pump laser via a 980/1550-nm WDM coupler. The EDF has a mode-field diameter of $5.9 \text{ }\mu\text{m}$ and a peak absorption of $\sim 6 \text{ dB/m}$ at 1530 nm. The WDM coupler comes with a 0.66-m-long HI1060 fiber pigtail with $\beta^{(2)}$ of $+20 \text{ ps}^2/\text{km}$. A polarization-insensitive

optical isolator is applied to ensure unidirectional propagation of light in the cavity. A 20% of optical power is extracted from the laser cavity by a 80/20 coupler as the laser output. A fiber-based PC is included for optimizing the mode-locked condition. The CNT-SA is constructed by connecting two fixed connection/physical contact (FC/PC) connector ends, in which one of the connector ends is deposited with CNTs by optically-driven deposition method as described in Chapter 4.

Since the net cavity dispersion is crucial to the pulse dynamic in mode-locked fiber lasers, in the following, we start to figure out the working conditions and characteristics of mode-locked lasers in both frequency-domain and time-domain for lasers with distinct net cavity dispersion. The CNT-SA with the modulation depth of 12.5% is initially incorporated into the laser cavity. We then focus on investigating the impact of modulation depth of SAs on the mode-locked lasers with different net cavity dispersion, especially with the near-zero net cavity dispersion.

6.2.1 Mode-locked Lasers with Net Anomalous Cavity Dispersion

When the net cavity dispersion is anomalous (negative) with relatively large value, the laser can operate in conventional soliton regime. Fig. 6-2 shows the output spectrum of the mode-locked fiber laser when the net cavity dispersion $\beta_{net}^{(2)}$ is managed to be -0.2516 ps^2 . The mode-locking is self-started under a pump power as low as $\sim 4 \text{ mW}$, and the corresponding output power is -9.8 dBm . The repetition rate of the output pulse train is measured $\sim 7.8 \text{ MHz}$ that is corresponding to the total cavity length of $\sim 26.2 \text{ m}$, confirming that the laser operates in the mode-locking state.

Figure 6-2 Optical spectrum of pulses generated from the passively mode-locked fiber laser with net anomalous cavity dispersion.

As shown in the spectrum, the center wavelength (λ_c) is located at ~ 1561 nm and the spectral bandwidth is estimated to be ~ 5.25 nm. Two pairs of sharp spectral peaks are superimposed on the spectrum. When adjusting the polarization controller, the spectrum remains the shape while the location of the first pair of spectral peaks (close to the center wavelength) can be remarkably shifted. On the contrary, the location of the second pair of sidebands is relatively fixed, which is ~ 8.85 nm away from the center wavelength. When the soliton propagates inside the laser cavity, it encounters various periodic perturbations, for instance, filtering, gain, and output coupling. The dispersive wave originated from the periodic perturbations can exchange energy from the propagating soliton at the discrete resonance wavelengths where the phase matching occurs, leading to the Kelly-sidebands in the spectrum. According to the soliton perturbation theorem, the location of Kelly-sidebands can be written by [55]:

$$\Delta\lambda = \frac{1.763\lambda_c^2}{2\pi c\tau} \sqrt{\frac{2\pi\tau^2}{|\beta_{net}^{(2)}|} - 1} \quad (6-1)$$

where $\tau = 0.567\tau_{FWHM}$. τ_{FWHM} is the pulse width, which is measured to be ~ 570 fs for the constructed laser. Hence, the location of the Kelly-sidebands is calculated to be ~ 8.82 nm, which is corresponding to the second pair of sharp spectral peaks. The strong Kelly-sidebands superimposed on the spectrum are the evidence that the soliton-like pulses propagate inside the laser cavity [55].

Figure 6-3 Autocorrelation trace of pulses generated from the passively mode-locked fiber laser with net anomalous cavity dispersion.

The temporal profile of the laser output is measured by an autocorrelator with a resolution of ~ 25 fs. The pulse width is estimated to be 570 fs, which is fitted by a sech^2 -shape pulse as shown in Fig. 6-3. The time-bandwidth product ($\Delta f \cdot \tau_{FWHM}$) of the pulse is calculated to be ~ 0.374 , which is close to the transform-limited sech^2 -pulse with $\Delta f \cdot \tau_{FWHM}$ of 0.315, indicating that the produced pulse is nearly chirp-free. The single-

pulse energy is calculated to be ~14 pJ. When we further increase the pump power, the laser tends to produce multiple pulses with equal pulse energy but random pulse-to-pulse spacing. Based on soliton-area theorem, the single-pulse energy is given by:

$$E = \frac{2|\beta_{net}^{(2)}|}{\gamma\tau_{FWHM}} \quad (6-2)$$

in which γ is effective nonlinearity parameter. It indicates that the product of pulse energy and pulse width is constant once the laser is constructed. The pulse width cannot be shortened infinitely due to the finite spectral bandwidth of the laser, therefore, the maximum of single-pulse energy is limited. In order to scale up the pulse energy, either the effective nonlinearity is reduced or the anomalous dispersion is increased.

From the experimental results, one can get the general characteristics of the dispersion-managed mode-locked fiber lasers with net anomalous cavity dispersion. Such lasers could generate the broadband spectrum with the superimposition of Kelly-sidebands in frequency-domain and the nearly chirp-free pulse with short pulse width in time domain. In addition, the single-pulse energy is limited.

6.2.2 Mode-locked Lasers with Net Normal Cavity Dispersion

When managing the net cavity dispersion with net normal (positive) dispersion by shortening the length of standard SMF, the mode-locked fiber laser can operate in dissipative soliton regime. Fig. 6-4 shows the output spectrum of the mode-locked fiber laser with the net cavity dispersion of $+0.029 \text{ ps}^2$ under the pump power of ~17 mW and the corresponding output power of ~0.7 dBm. Different from the laser with net anomalous dispersion, the spectrum shows the steep edges for the laser with net normal dispersion. The center of the spectrum is located at ~1562 nm

and the spectral bandwidth is estimated to be ~ 8.6 nm. When adjusting the polarization controller, CW spikes could superimpose on the flattop of the spectrum that induces the laser to be unstable. It indicates that the mode-locked fiber laser at net normal dispersion region is sensitive to the change of polarization.

Figure 6-4 Optical spectrum of pulses generated from the passively mode-locked fiber laser with net normal cavity dispersion.

The autocorrelation trace of the output pulse is measured as shown in Fig. 6-5. The pulse width is estimated to be ~ 51 ps with a Gaussian-shaped pulse fitting, which is much larger than the pulse produced from the laser with net anomalous dispersion. The time-bandwidth product is calculated to be ~ 53.75 , indicating that the pulse is highly frequency-chirped in the laser with net normal dispersion. The corresponding pulse energy is calculated to be ~ 86 pJ that is almost 6.1 times as high as the pulse energy generated from the laser with net anomalous dispersion as shown in Fig. 6-3.

Figure 6-5 Autocorrelation trace of pulses generated from the passively mode-locked fiber laser with net normal cavity dispersion.

Figure 6-6 Pulse-width-compression by dispersion-compensation.

Since the output pulse is highly frequency-chirped, the pulse width could be further compressed by using a fiber with the opposite dispersion to de-chirp the pulse. Due to

the up-chirp of pulse produced after the normal-dispersion EDF, we use the standard SMF with a GVD parameter of $\sim 22 \text{ ps}^2/\text{km}$ to de-chirp the pulse. Fig. 6-6 shows the result of the compressed pulse width in the relationship of the length of SMF. As the length of SMF increases, the pulse width is greatly decreased and then slightly increased due to the excessive dispersion. The shortest pulse width can be obtained with total GVD parameter of $\sim 11.79 \text{ ps}^2$ corresponding to the optimized length of $\sim 536 \text{ m}$. Fig. 6-7 shows the corresponding autocorrelation trace of the output pulse showing the pulse width of $\sim 870 \text{ fs}$. The pedestal superimposed on the temporal profile is due to the third-order dispersion [125].

Figure 6-7 Autocorrelation trace of pulses after compression.

From the obtained results, one can find the features of the mode-locked fiber lasers with net normal cavity dispersion. In contrast to the mode-locked fiber laser with net anomalous dispersion, the lasers with net normal cavity dispersion could generate the square-shape spectrum with the steep-edges in frequency-domain and the highly-chirped

pulse with wide pulse width in time domain. The single-pulse energy is relatively high, and the pulse width could be further compressed outside the laser cavity.

6.2.3 Mode-locked Lasers with Net Cavity Dispersion Near Zero

When the net cavity dispersion is managed close to zero, the mode-locked fiber laser can operate in dispersion-managed soliton regime (also named stretched pulses). Different from the conventional soliton regime where the anomalous dispersion fiber dominates for pulse shaping as well as the dissipative regime in which the normal dispersion fiber dominates, the two opposite dispersion fibers take the equal role for pulse shaping in dispersion-managed soliton regime.

Figure 6-8 Optical spectrum of pulses generated from the passively mode-locked fiber laser with net cavity dispersion near zero.

Fig. 6-8 shows the optical spectrum of the developed mode-locked fiber laser with the net cavity dispersion of -0.158 ps^2 . The pump threshold of mode-locking is found to be

~4 mW with an output power of ~-10.1 dBm. The center of the optical spectrum is located at ~1561.7 nm and the spectral bandwidth is estimated to be ~6.8 nm. The shape of spectrum is nearly Gaussian with two small spectral peaks. The spectral peaks can be shifted by adjusting the polarization controller. The relatively clean spectrum without the strong Kelly-sidebands indicates that the energy exchange between the dispersive wave and the pulse is weak [49]. Since pulse is stretched and compressed by the opposite dispersion fibers in one round trip, the pulse dynamic diminishes the phase matching between soliton and dispersive wave. The autocorrelation trace of the output pulse is given in Fig. 6-9. The pulse width is estimated to be 450 fs, in which the pulse is fitted by a sech^2 -shaped pulse. The time-bandwidth product is calculated around 0.382. The corresponding pulse energy is calculated to be ~11 pJ.

Figure 6-9 Autocorrelation trace of pulses generated from the passively mode-locked fiber laser with net cavity dispersion near zero.

By further increasing the net cavity dispersion to zero point (-0.114ps^2), the output spectrum of the laser has a nearly triangular shape as shown in Fig. 6-10. A continuous-wave spike is superimposed on the center of spectrum, which results in the spectral bandwidth less than $\sim 0.1\text{ nm}$. In this case, the laser only produces random pulse bursts instead of stable pulse trains no matter how carefully the pump power as well as the state of polarization controller are adjusted.

Figure 6-10 Optical spectrum of pulses generated from the passively mode-locked fiber laser with net cavity dispersion close to zero.

For mode-locked fiber lasers with net cavity dispersion near zero, the optical spectrum is Gaussian-like shape with relatively broad spectral bandwidth. The produced pulses have shorter pulse width than conventional soliton and dissipative soliton. However, the laser tends to be unstable when the net cavity dispersion is very close to zero.

In section 6.2.1-6.2.3, we have separately investigated the working conditions and the characteristics of mode-locked fiber lasers with various net cavity dispersions by

incorporating CNT-SAs. When the net cavity dispersion is anomalous, the output spectrum of mode-locked fiber lasers shows Kelly-sidebands and the pulse is nearly chirp-free. However, the produced pulse energy is limited. Such lasers are regarded to be operating in conventional soliton regime because the pulse formation is dominated by the interplay between the anomalous dispersion and fiber optical Kerr nonlinearity. For the mode-locked fiber lasers with net normal dispersion, the output spectra show the square shape and steep edges. The produced pulses are highly chirped with higher pulse energy, which are noted as dissipative solitons. When the net cavity dispersion is near zero, the output spectrum of mode-locked laser is Gaussian-shape with very large spectral bandwidth. The produced pulses exhibit narrow pulse width. However, the laser is unstable when the net cavity dispersion is very close to zero.

6.2.4 Enhanced Stability of Dispersion-Managed Mode-locked Fiber Lasers by High-contrast CNT-SAs

According to our studies, a dispersion gap near net zero cavity dispersion is observed where the laser only produces random pulse bursts instead of stable pulse trains. In order to figure out the originality of such laser instability, we investigate the performance of mode-locked fiber laser across the whole net cavity dispersion region with different CNT-SAs. The experimental setup is the same as the one shown in Fig. 6-1. The increase of the modulation depth of CNT-SAs is achieved by depositing different amount of CNTs on fiber ends by optically-driven deposition method. In this work, two CNT-SAs with modulation depths of 12.5% and 6.4% are

employed, exhibiting non-saturable losses of 47% and 28.1%, respectively. $\beta_{net}^{(2)}$ is changed from -0.31 to +0.04 ps² by shortening the length of the SMF in the laser cavity.

Figure 6-11 Spectra of the mode-locked lasers at different net cavity dispersion incorporating CNT-SAs with modulation depths of (a) 12.5 % and (b) 6.4 %

Fig. 6-11(a) shows the spectral evolution of the mode-locked lasers against various net cavity dispersions when the SA with modulation depth of 12.5 % is incorporated. The Kelly-sidebands on the spectrum are found to gradually move away from the center wavelength while the spectral shape turns into nearly Gaussian-shape associated with spectrum broadening when the net cavity dispersion approaches zero. The spectra show broad spectral bandwidth and operate

stably when the net cavity dispersion is either smaller than -0.158ps^2 or larger than $+0.029\text{ps}^2$. No matter how carefully we play with pump power and polarization controller, only unstable spectra superimposed by CW spikes are observed when the net cavity dispersion of fiber laser falls in between -0.158ps^2 and $+0.029\text{ps}^2$.

The same experiment is repeated using the same fiber laser incorporating the CNT-SA with modulation depth of 6.4% as shown in Fig. 6-11(b). When the net cavity dispersion approaches the value of -0.233ps^2 , the Kelly-sidebands on the spectrum are found to gradually move away from the center wavelength while the spectral shape turns into nearly Gaussian-shape together with spectrum broadening. When the net cavity dispersion is further increased to zero value, the CW spike cannot be suppressed. If the net cavity dispersion is larger than $+0.039\text{ps}^2$, dissipative solitons with square-shape spectra is observed.

Figure 6-12 Spectral bandwidth against net cavity dispersion of the mode-locked fiber laser using CNT-SAs with different modulation depths.

For comparison, Fig. 6-12 plots spectral bandwidth against net cavity dispersion for mode-locked lasers with the two different CNT-SAs. When the absolute value of $\beta_{net}^{(2)}$ is close to zero, the spectral bandwidth gradually increases and then sharply decreases. The significant decrease in the spectral bandwidth is a reflection of the unstable operation of the laser. For the fiber laser incorporating a CNT-SA with modulation depth of 6.4%, the unstable region is found to be in the range of $-0.233 ps^2 < \beta_{net}^{(2)} < +0.039 ps^2$. On the other hand, for the case of CNT-SA with modulation depth of 12.5%, the unstable region of the laser is measured in the range of $-0.158 ps^2 < \beta_{net}^{(2)} < +0.029 ps^2$. The results show that the unstable region of the dispersion-managed mode-locked fiber laser could be shrunk by ~31.3% when the modulation depth of the SA is increased from 6.4% to 12.5%.

Figure 6-13 Pulse width against net cavity dispersion of the mode-locked fiber laser using CNT-SAs with different modulation depths.

Fig. 6-13 illustrates the measured pulse width versus $\beta_{net}^{(2)}$ in the net anomalous dispersion regime. The pulse width decreases as $\beta_{net}^{(2)}$ approaches zero. The shortest pulse width is obtained around 450 fs with $\beta_{net}^{(2)}$ of -0.158 ps² when the CNT-SA with modulation depth of 12.5% is applied.

According to the obtained results shown in Fig. 6-12, we can conclude that a dispersion gap near zero net cavity dispersion exists where the mode-locked fiber tends to be unstable. Even though we can see the direct relevance between the laser instability and the modulation depth of a SA, the difficulty is to confirm whether the observed instability near net zero dispersion caused only by the small modulation depth of CNT-SAs. From the studies in Sections 6.2.1-6.2.3, the mode-locking state of a dispersion-managed fiber laser is achieved by satisfying the conditions: a sufficient pump power, an appropriate polarization state, a proper modulation depth of SA, a weak spectral filtering, relatively small cavity loss, and enough Kerr nonlinearity. On the contrary, any failure to fulfill above requirements could be a cause of the laser instability. Although we plan to maintain all above factors unchanged except the modulation depth of CNT-SAs, it is difficult to change solely one parameter in the experiment. For example, adjusting polarization state might induce the change of spectral filtering; tuning pump power may change the accumulated Kerr nonlinearity; and replacing saturable absorber could change the cavity loss. In order to clarify whether the modulation depth of CNT-SA plays the most important role in stabilizing mode-locking operation or not, further numerical studies are necessary.

6.3 Numerical Analysis and Discussion

Numerical simulation is performed to qualitatively analyze the role of SA in a dispersion-managed fiber laser. The cavity layout in the simulation is shown in Fig. 6-14, which is similar with the experimental setup shown in Fig. 6-1. A piece of gain fiber with normal dispersion is connected to a HI1060 fiber. A portion of optical power is extracted as laser output by an output coupler. The length of SMF with anomalous dispersion after the SA is adjusted to manage $\beta_{net}^{(2)}$. The outcome of the present loop calculation is set to be an input of the next loop.

Figure 6-14 Cavity layout in simulation analysis: output coupler (OC).

In the simulation, Ginzburg-Laudau Equation given in Eq. (3-46) is chosen as the model to simulate light propagation in EDF, HI1060 fiber and SMF. The intensity-dependent transmittance $T(I)$ of a fast SA is expressed by:

$$T(I) = 1 - (\alpha_0 / (1 + I/I_{sat}) + \alpha_{ns}) \quad (6-3)$$

where I is the instantaneous intensity of the pulse; I_{sat} is the saturation intensity of SA; α_0 represents the modulation depth of SA; and α_{ns} refers to the non-saturable loss. Provided that L_i refers to the fiber length and i stands for each fiber section, the net cavity dispersion $\beta_{net}^{(2)}$ can be given by:

$$\beta_{net}^{(2)} = \sum_i L_i \times \beta_i^{(2)} \quad (6-4)$$

The simulation parameters for each fiber section are listed in Table 6-1. The laser is named as ML_1. The gain bandwidth is $\Omega_g = 5.5$ THz. In order to investigate specifically the influence of the modulation depth on the stability of dispersion-managed mode-locked fiber lasers, only a_0 and L_{SMF} are changed while the other parameters are kept constant. I_{sat} is set to be 10 MW/cm² referring to the typical value of CNT-SAs [8]. α_{ns} is assumed to be 15% corresponding to the minimum non-saturable loss of CNT-SA with a desirable modulation depth obtained in our experiments.

The Ginzburg-Laudau Equation is solved with a standard split-step Fourier algorithm as described in Section 3.2. The initial seed is an arbitrary weak pulse. The temporal resolution, spatial resolution, and frequency resolution are set to be 1 fs, 1 cm and 0.244 THz, respectively.

Table 6-1 Summary of Simulation Parameters for ML_1

Fiber type	$\beta^{(2)}$ (ps ² /km)	γ (W ⁻¹ km ⁻¹)	L(m)	g_0	P_{sat} (mW)
EDF	+23.4	2.69	7.32	2	5
HI1060	+20	1.5	0.66	0	0
SMF	-22	1.06	Variable	0	0

6.3.1 The Role of Net Cavity Dispersion

In mode-locked fiber system, pulse could experience amplification, loss, dispersion and Kerr nonlinear effect as shown schematically in Fig. 6-15. Provided that the pulse stabilization is reached by the interplay between chromatic dispersion and Kerr nonlinear effect, the laser system is regarded to be lossless. On the other hand, if gain and loss anticipate the stabilization

of pulse, the laser system is considered dissipative. The interplay among these effects mainly depends on the net cavity dispersion. In the following, we numerically calculate the optical spectra in frequency-domain and the pulse profile in time-domain for the lasers with various net cavity dispersions when modulation depth of SA is 12.5%, and discuss the mechanism of pulse formation in the corresponding regime.

Figure 6-15 Schematic diagram of the interplay among various effects in passively mode-locked fiber lasers.

Figs. 6-16(a) and (b) show the spectral and temporal profiles of the mode-locked fiber laser with $\beta_{net}^{(2)} = -0.172 \text{ ps}^2$. In frequency-domain, the periodic pairs of sidebands are superimposed on the spectrum. In time domain, the output sech^2 -fitted pulse shows minor frequency-chirp as plotted. In this regime, the soliton-like pulse formation is mainly originated from the interplay between the anomalous dispersion and the nonlinear optical Kerr effect of fiber. The anomalous dispersion will result in the pulse with down-chirp, while the self-phase modulation originated from the Kerr nonlinear effect induces the pulse with up-chirp. As a result, the two opposite effects can cancel each other and lead to the shape-unchanged pulse with chirp-free, named as

soliton. The gain and loss are considered as the periodic perturbations, which induce the dispersive wave to exchange energy from the soliton at the resonant frequencies or wavelengths.

Figure 6-16 Calculation of (a) spectral and (b) temporal profiles of the mode-locked fiber laser with net anomalous cavity dispersion.

For $\beta_{net}^{(2)} = -0.028 ps^2$, the spectral shape is nearly-Gaussian associated with a wide spectral bandwidth as shown in Fig. 6-17(a). The corresponding pulse shows a Gaussian-profile with a shorter pulse width and a purely linear frequency-chirp as shown in Fig. 6-17(b). The up-chirp is due to the output after the normal-dispersion gain fiber.

Figure 6-17 Calculation of (a) spectral and (b) temporal profiles of the mode-locked fiber laser with net cavity dispersion near zero.

By further increasing $\beta_{net}^{(2)}$ to $+0.02 \text{ ps}^2$, an output spectrum with steep edges is obtained as given in Fig. 6-18(a). Fig. 6-18(b) presents the corresponding pulse that is highly chirped with a relatively wide pulse width. In net normal dispersion region, both the dispersion effect and the Kerr nonlinear effect of fibers induce the pulse with up-chirp. When only these two effects dominate, the pulse keeps broadening. However, the spectral filtering effect can shorten the pulse width by cutting the wings of the pulses because the pulse is frequency-chirped. The stabilization of the pulse in fiber lasers with net normal dispersion is attributed to interplay among the effects of dispersion, nonlinearity, gain and loss. Since the spectral filtering plays an important role in the pulse stabilization, the system is considered to be dissipative [126].

Figure 6-18 Calculation of (a) spectral and (b) temporal profiles of the mode-locked fiber laser with net normal cavity dispersion.

Fig. 6-19(a) shows the optical spectrum of fiber laser with $\beta_{net}^{(2)}$ of -0.001 ps^2 . A small CW spike is superimposed on the spectrum at the center wavelength, while no stable pulse can be maintained in time-domain. Although it is difficult to precisely estimate the parameter values from the real laser cavity, one can find the general

agreement with the experimental observation. Fig. 6-19(b) further plots the evolution of the spectral bandwidth and the peak power of the pulse against cavity round-trip. In the beginning, the initial pulse reshaped by a SA from amplified spontaneous emission (ASE) noise is amplified by a gain fiber associated with an increase of pulse peak power. The spectral bandwidth broadens by self-phase modulation. As the spectral bandwidth gets wider, the spectrum-filtering plays an increasingly important role which in turn increases loss and decreases the peak power of the pulse. When the cavity loss deviates substantially and cannot be caught up by the cavity gain, the pulse energy is gradually shed away and the peak power of the pulse is correspondingly decreased. As a result, the weak nonlinear effect is insufficient to support broadband mode-locking operation and leads to the unstable CW emission.

Figure 6-19 Calculation of (a) spectral profile of the mode-locked fiber laser with net cavity dispersion close to zero, and (b) bandwidth and peak power evolution against cavity round trip.

Fig. 6-20 shows the corresponding pulse evolution in time-domain. The pulse is gradually dispersed after circulating in the cavity for hundreds of round trips. In order to

reshape the pulse to achieve a desirable peak power, a SA with large modulation depth is necessary.

Figure 6-20 Calculation of pulse evolution against cavity round trip in mode-locked fiber laser with net cavity dispersion close to zero

Since the same $\beta_{net}^{(2)}$ can be designed by various combinations of fibers, we also numerically analyze the dispersion-managed fiber laser with the same SA but different fiber parameters. A mode-locked fiber laser (ML_2) with a same SA as ML_1 but a very short cavity length of 2.39 m is constructed for comparison. Table 6-2 lists the parameters of ML_2 in the simulation and the gain bandwidth is set as $\Omega_g = 10$ THz. The relationship between the spectral bandwidth and $\beta_{net}^{(2)}$ for ML_1 and ML_2 is shown in Fig. 6-21. Although the two mode-locked lasers have different cavity length, one can observe the general trend of lasers in which the bandwidth is initially increased and then significantly decreased when the absolute value of the net cavity dispersion is close to zero. Therefore, the total length of laser cavity is not the

major reason that causes the laser instability. As the accumulated Kerr nonlinearity is proportional to the fiber length, the numerical results also indicate that the change of accumulated Kerr nonlinearity is not the major reason that causes the laser instability.

Table 6-2 Summary of Simulation Parameters for ML_2

Fiber type	$\beta^{(2)}$ (ps ² /km)	γ (W ⁻¹ km ⁻¹)	L(m)	g_0	P_{sat} (mW)
EDF	+12	2	0.39	120	100
HI1060	+20	1.5	2	0	0
SMF	-22	1.06	Variable	0	0

Figure 6-21 Spectral bandwidth against net cavity dispersion for two sets of mode-locked fiber lasers.

The influence of the location of CNT-SA in the dispersion map of laser is also investigated. The curve of ML_1 in Fig. 6-22 refers to the spectral bandwidth of mode-locked fiber laser with CNT-SA located before the anomalous dispersion fiber whose cavity layout is shown in Fig. 6-

14. The curve of ML_3 presents the spectral bandwidth of mode-locked fiber laser with CNT-SA located after the anomalous dispersion fiber. The two curves have similar trend which have a large suppression band near zero net cavity dispersion, indicating that the location of CNT-SA in dispersion map has little influence in the optimization results.

Figure 6-22 Spectral bandwidth against net cavity dispersion for mode-locked fiber lasers with different locations of CNT-SA.

In a dispersion-managed mode-locked fiber laser, spectral filtering plays an important role as the spectrum broadens when $\beta_{net}^{(2)}$ approaches zero which affects the laser stability. Since the loss experienced by the pulse with a large spectral bandwidth is greater than that by continuum wave (CW) due to spectral filtering, CW could break through the pulse and causes instabilities. As a result, limits the achievement of stable mode-locking with $\beta_{net}^{(2)}$ towards zero. In order to compensate for the loss induced by the spectral filtering, one solution is to adopt SAs with more absorption to CW than to high-intensity pulses in the laser cavities. In the following, the influence of spectral

filtering as well as SAs on stability of dispersion-managed mode-locked fiber lasers with near-zero net cavity dispersion is investigated.

6.3.2 The Role of Spectral Filtering

As the spectral bandwidth of the laser gets wider when $\beta_{net}^{(2)}$ approaches zero, the strong spectral filtering effect could introduce additional loss to the pulse in comparison to a continuous wave due to that the former has large bandwidth. Consequently, the continuous wave might grow while the pulse are suppressed, which induces the laser to be unstable. Although there is no obvious spectral filter inside the laser cavity, the finite bandwidth of gain medium can contribute to the spectral filtering. The narrow gain bandwidth is responsible for strong spectral filtering. In order to investigate the impact of spectral filtering on the stability of mode-locked lasers, Fig. 6-23 shows the spectral bandwidth against net cavity dispersion for mode-locked laser (ML_1) with different gain bandwidth. By increasing the gain bandwidth, the unstable region of fiber laser is shrunk. This further verifies that the origin of the instabilities is related to the strong spectral filtering. Note that the unstable region of the fiber laser with $a_0 = 12.5\%$ can also be minimized by setting the gain bandwidth to 12.5 THz.

The influence of spectral filtering on mode-locked lasers with net anomalous dispersion and net normal dispersion can be also studied from Fig. 6-23. For the mode-locked lasers operate in the conventional soliton regime with relatively large net anomalous dispersion, the spectral bandwidths show minor difference in the lasers with distinct gain bandwidths. Such minor change of spectral bandwidth implies that the

pulse formation and stabilization is less dependent on spectral filtering. On the contrary, when the mode-locked lasers operate in dissipative soliton regime with relatively large net normal dispersion, the spectral bandwidths have notable difference for lasers with different gain bandwidths. Interesting, the smaller gain bandwidth (5.5 THz) leads to larger spectral bandwidth since the pulse shortening is dependent on spectral filtering.

Figure 6-23 Spectral bandwidth against net cavity dispersion for mode-locked fiber lasers with distinct gain bandwidth.

6.3.3 Optimization of Modulation Depth of SAs

Since the gain bandwidth is fixed once the gain fiber is chosen, the alternative method to shrink the unstable region of mode-locked laser is to apply SAs with large modulation depths. Fig. 6-24 shows the spectral bandwidth of the laser against $\beta_{net}^{(2)}$ when the modulation depths of SAs are 6.4%, 12.5%, and 20%. The unstable region of the mode-locking operation can be shrunk by ~36% for the laser incorporating SAs with $a_0 = 12.5\%$

replacing of $a_0 = 6.4\%$. For the evidence that the SA with a larger modulation depth can help the laser to shrink the unstable region, the numerical results are in good consistent with the experimental observations. The results demonstrate that SAs play important roles not only in the initialization of pulse formation but also in the stabilization of pulse formation for the laser with $\beta_{net}^{(2)}$ near zero. In the case of a SA with modulation depth of 20%, the dispersion-managed fiber laser can operate in the stably mode-locking state across the entire dispersion regime. On the other hand, it is observed that for a large a_0 , the spectral bandwidth tends to decrease near zero $\beta_{net}^{(2)}$. It implies that the residual saturable absorption could contribute to the cavity loss, which might decrease the threshold for Q-switching instability [74].

Figure 6-24 Spectral bandwidth against net cavity dispersion for mode-locked fiber lasers using SAs with distinct modulation depths.

As the modulation depth of SAs is crucial to the pulse stabilization in dispersion-managed mode-locked lasers, it is meaningful to figure out the relationship between the

modulation depth and the net cavity dispersion for stable mode-locking operation. Fig. 6-25 plots the boundary of the mode-locked fiber laser (ML_1) between the unstable region and stable region in the relationship of the modulation depth of SAs. It shows that the larger modulation depth of SA is required for the stably mode-locked lasers with smaller net cavity dispersion. In order to obtain laser mode-locking with minimum unstable region and avoiding residual saturable absorption, the modulation depth is optimized at 16% for the given cavity parameters. In the following chapter, a much reduced instability of dispersion-managed mode-locked fiber laser with a small net cavity dispersion of $\sim -0.016 \text{ ps}^2$ is experimentally demonstrated by using a CNT-SA with a large modulation depth of 15%. Such a significant reduction of net cavity dispersion from -0.158 ps^2 to -0.016 ps^2 by changing the modulation depth of SAs from 12.5% to 15% in the experimental observations further confirms the optimized results.

Figure 6-25 Optimization of modulation depth of SAs for stable mode-locking operation.

6.4 Summary

In this Chapter, we have investigated the stability of dispersion-managed mode-locked fiber laser with net cavity dispersion near-zero by using carbon-nanotube-based saturable absorbers with different modulation depths. Experimental results demonstrate that the unstable region of the stretched-pulse mode-locked fiber laser can be reduced by ~31.3% when modulation depth of SAs is increased from 6.4% to 12.5%. The SAs with large modulation depth can assist laser cavity to stabilize the mode-locking operation. The simulated results are consistent with the experimental observation, which can be a general guidance for the similar dispersion-managed fiber laser system.

Chapter 7 CNT-SAs Incorporated Dispersion-managed Mode-locked Fiber Lasers for Flat Supercontinuum Generation

In this chapter, we extend the application of 1.55- μm dispersion-managed mode-locked fiber laser incorporating single-walled carbon-nanotube-based saturable absorber for flat supercontinuum (SC) generation.

7.1 Introduction

The generation of new frequency components and the spectral broadening are inherent features of nonlinear optics, and have been investigated intensively since 1960s. Supercontinuum (SC) generation has found wide applications covering the fields of optical communication, nonlinear optics, fluorescent microscopy, spectroscopy, and medicine. In general, a SC is generated by launching an ultrashort pulse train from a mode-locked laser into a highly nonlinear fiber to induce spectral broadening [127-130]. The qualities of ultrashort pulse train and nonlinear medium determine the performance of SC. Ultrashort pulses can be generated from a passively mode-locked laser with typical pulse width ranging from ps to fs. To construct a passively mode-locked laser, a semiconductor saturable absorber (SA) is a key component to reshape and stabilize optical pulses. Recently, CNTs have emerged as SAs in mode-locked lasers due to their intrinsic optical property of saturable absorption. The CNT-SA incorporated mode-locked fiber lasers as selected pump sources for SC generation have several advantages over the conventional mode-locked fiber lasers that are based on nonlinear polarization

rotation (NPR) and nonlinear optical loop mirror (NOLM). Firstly, CNT-SAs can benefit mode-locked fiber lasers with polarization-insensitive feature thereby mode-locked fiber lasers are relatively stable to environmental disturbance. Secondly, CNT-SAs can be footprint and thin thickness which benefit the mode-locked fiber lasers with very compact cavity design for high-repetition-rate pulse generation. In addition, CNT-SAs have certainty of modulation depth and are of independence on cavity setting which enables the mode-locked fiber lasers to be optimized through the management of fiber nonlinearity and dispersion. Moreover, compared to those semiconductor saturable absorber mirror (SESAM), CNT-SAs could work in bidirectional modes and thereby mode-locked fiber lasers can be bidirectional operation [69].

In addition to a proper pulsed light source, a suitable highly nonlinear fiber is important for the optical spectral broadening. However, such fiber-based SC generation usually operates near the zero-dispersion wavelength of the fiber which leads to significant ripples and fluctuation in the output SC spectrum [127]. One way to obtain flat and efficient SC is using a fiber with well-controlled normal dispersion and high nonlinearity [129, 131].

In this chapter, a mode-locked fiber laser incorporating a CNT-SA is chosen as the pulsed laser source for SC generation. The mode-locked fiber laser with a short-cavity length is dispersion-managed having the net cavity dispersion close to zero. The pulse trains generated from the CNT-based dispersion-managed mode-locked laser exhibit a high repetition rate of 123 MHz, a low timing jitter of 35 fs and a narrow pulse width of 620 fs. The generated femtosecond pulse train is launched into a normal dispersion highly nonlinear photonic crystal fiber (PCF) for SC generation. Since the pulse train

propagates in the normal dispersion regime of the PCF only, linear frequency chirp is induced by self-phase modulation which leads to a flat SC ranging from 1450 nm to 1650 nm at -20-dB power level. The experimental results of the spectral broadening in the PCF are found to be consistent with the theoretical investigation by solving nonlinear Schrödinger equation.

7.2 Dispersion-managed Mode-locked Fiber Lasers Incorporating CNT-SAs

In mode-locking, the random phase relations of cavity longitudinal modes are fixed, resulting in a single pulse, and its repetition rate corresponding to the inverse of the cavity round trip time. Many aspects including the dispersive and nonlinear properties of the intra-cavity components need to be balanced in order to achieve stable operation. The basic mechanism is easily understood by considering a SA with various absorption during the time span of pulse width. When an optical pulse propagates through such an absorber, its wings experience more loss than the central part, which is intense enough to saturate the absorber. The pulse continuous to shorten until it becomes so short that its spectral width is comparable to the gain bandwidth, thus stable output pulse with specific pulse width could be obtained. In the following, we develop a low-jitter dispersion-managed mode-locked fiber laser for the source of SC generation.

7.2.1 Experimental Setup

Fig. 7-1 shows the experimental setup of passively mode-locked fiber laser incorporating a CNT-SA, in which the CNT-film is applied to the end-facet of

connection/physical contact (FC/PC) connectors to ensure CNT-light interaction. Such CNT-SA has the modulation depth of ~15% and the non-saturation loss of ~46%. A WDM coupler is used to launch a 976 nm pump light into the laser cavity from a pumping laser diode. A 0.31-m-long piece of EDF (LIKKIE 110) is used as the gain medium in the cavity. A polarization controller is used to adjust and optimize the mode-locking condition in the cavity. An optical isolator is applied to ensure unidirectional operation of the laser cavity, and 10% of the optical power is coupled out from the cavity through an optical coupler as an output. The dispersion map of the mode-locked fiber laser is plotted in Fig. 7-2. The total length of the laser cavity is ~1.67 m with a total net cavity dispersion of -0.016 ps^2 .

Figure 7-1 Experimental setup for dispersion-managed mode-locked fiber laser incorporating CNT-SA.

Figure 7-2 Dispersion map of the constructed mode-locked fiber laser.

7.2.2 Experimental Results

In the experiment, self-starting of the mode-locked fiber laser is obtained at an input pump power of ~ 52 mW with an output average power of 0.3 mW. Fig. 7-3 shows the optical spectrum with center wavelength of ~ 1562 nm and spectral bandwidth of 6.58 nm. Since the net cavity dispersion is close to zero, the Kelly-sidebands are far away from center wavelength of the optical spectrum. Based on the transform-limited pulse calculation, the non-chirp pulse width is estimated to be ~ 393 fs. Fig. 7-4 depicts the corresponding RF spectrum, respectively. The figure shows that the output pulses have an extinction ratio of around ~ 65 dB at a fundamental frequency of 123 MHz corresponding to the cavity length.

Figure 7-3 Output spectrum of pulses generated from the mode-locked fiber laser.

Figure 7-4 RF spectrum of pulse trains generated from the mode-locked fiber laser.

As the amplified stimulated emission (ASE)-induced center wavelength changes are coupled to timing jitter via the group velocity dispersion, pulse train with low timing could be produced from the dispersion-managed fiber laser with net cavity dispersion near zero [116, 117, 132]. We investigate the timing jitter noise of developed fiber laser

by using a signal source analyzer (SSA). The root mean square (rms) timing jitter Δt is obtained by measuring the Power Spectral Density (PSD) of $S_p(f)$ around the n^{th} harmonic between a specific offset frequency range $[f_L, f_H]$ and calculated by using the following relation:

$$\Delta t = \frac{1}{2\pi f_{rep}} \sqrt{\int_{f_L}^{f_H} S_p(f) df} \quad (7-1)$$

Figure 7-5 Noise spectrum of pulse trains from the mode-locked fiber laser.

Fig. 7-5 presents the phase noise spectrum between 10 Hz to 10 MHz frequency offset range that is measured around the fundamental harmonic frequency. The rms timing jitter is calculated to be approximately 35 fs. The fiber laser is tested for its stability by running for several hours and we observed little or no fluctuations in its timing jitter. This clearly indicates excellent long-term stability and low noise performance from the CNT-based mode-locked fiber laser.

7.3 Flat Supercontinuum Generation by Using Highly-nonlinear

Photonic Crystal Fibers

7.3.1 Experimental Setup

In order to boost the peak power of the pulse generated from the mode-locked laser, an EDFA with a normal dispersion gain fiber is utilized as shown in Fig. 7-6. Since the pulses undergo dispersion-induced chirp through EDFA, a certain length of standard SMF with anomalous dispersion is inserted after the EDFA to compress the pulses. The pulse width against the length of SMF ranging from 3.2 m to 1.2 m is measured by a commercial autocorrelator. The compressed ultrashort pulses are further applied for the SC generation. A piece of 15-m-long normal dispersion highly-nonlinear PCF is used as the nonlinear medium. The PCF has a three-fold symmetric hybrid core region with the nonlinearity coefficient of $11 \text{ (W}\cdot\text{km)}^{-1}$ and the core diameter of $1.5 \text{ }\mu\text{m}$ and as shown in Fig. 7-7(a). The attenuation of the fiber is less than 10 dB/km. By varying the hole size and pitch of the fiber, one can tailor the dispersion characteristics. The second-order dispersion of PCF is given in Fig. 7-7(b). The overall dispersion of this PCF is flat and well-controlled over the entire telecommunication band (less than $-3 \text{ ps}/(\text{km}\cdot\text{nm})$ over 1500-1600 nm) [133]. The dispersion variation is less than $1 \text{ ps}/(\text{km}\cdot\text{nm})$ in the range of 1465-1655 nm, with a dispersion slope of less than $1\times 10^{-3} \text{ ps}/(\text{km}\cdot\text{nm}^2)$ around the 1550 nm range.

Figure 7-6 Experimental setup for supercontinuum generation: mode-locked (ML); photonic crystal fiber (PCF).

Figure 7-7 (a) Geometry of the PCF and (b) the corresponding chromatic dispersion (reprint from [133])

7.3.2 Experimental Results

The inset of Fig. 7-8 shows the compressed pulse width against different lengths of SMF. The narrowest pulse width is optimized with the SMF length of 1.8 m. Fig. 7-8 plots the autocorrelation trace at the optimized length of SMF, in which the pulse width obtained is measured to be 620 fs by a sech^2 profile fitting.

Figure 7-8 Autocorrelation trace of pulses after compression.

The compressed pulses are then launched into this PCF, which induces a different value of phase shift at different time instants of the pulse, resulting in broadening of the output spectrum as shown in Fig. 7-9. By launching the compressed and amplified pulses into the PCF, a SC is generated ranging from 1450 nm to 1650 nm at -20-dB power level with a relatively low fluctuation of 7 dB throughout this range.

Figure 7-9 Supercontinuum generation at various average powers.

7.4 Theoretical Analysis and Discussion

Numerical investigation of the spectral broadening is performed by solving the nonlinear Schrödinger equation (NLSE) according to Eq. (3-27). An initial sech-pulse with a pulse width τ_{FWHM} of 620 fs and a peak power of 271 W is launched into a length of 15-m-long PCF. Since the length of fiber for SC generation is short ($\ll 1$ km), the terms related to fiber loss can be ignored in the calculation. The derivatives of the higher-order propagation constants are included, in which β_2 , β_3 and β_4 are set to be $0.6 \text{ ps}^2/\text{km}$, $-0.001 \text{ ps}^3/\text{km}$, and $1 \times 10^{-6} \text{ ps}^4/\text{km}$ at the center wavelength of 1560 nm, respectively. The nonlinearity of the PCF is assumed to be $11 \text{ (W} \cdot \text{km)}^{-1}$ corresponding to our measurements. In the simulation, the NLSE is solved with a standard split-step Fourier algorithm as described in Section 3.2. The temporal resolution, spatial resolution, and frequency resolution are set to be 2 fs, 0.3 cm and 0.1 THz, respectively.

Figure 7-10 Experimental and numerical results of supercontinuum generation.

The simulation results and the experimental results are plotted for comparison as shown in Fig. 7-10. One can observe that the simulation results are consistent to the experimental results. The power fluctuation of the spectrum arises mainly due to the SPM-induced chirp with the same instantaneous frequency value at two distinct time points [70]. The same frequency with different phases will interfere constructively or destructively. Comparing the measured and simulation results, the mismatched portions are due to the slight asymmetry of the seeding pulse launched into the PCF in the experiments. Fig. 7-11 shows time and spectrum evolution of the simulated SC generation. It indicates that the spectrum broadening is non-saturable when pulses with peak power of 271 W propagate in the 15-m-long PCF. With the generated pulses propagating through a normal dispersion medium, a flat SC can be obtained mainly from SPM.

Figure 7-11 Spectrum evolution of the simulated SC generation.

7.5 Summary

In this chapter, we investigate CNT-based mode-locked fiber laser for supercontinuum generation. We demonstrate a low noise ultra-fast mode-locked fiber laser with 3-dB bandwidth of 6.53 nm by incorporating a CNT-SA. A pulse train with pulse width of 620 fs and timing jitter of ~35 fs is obtained after pulse compression. To realize the spectral broadening, the obtained pulse train is launched into a dispersion-flattened normal dispersion high nonlinearity photonic crystal fiber. Experimentally, the output SC spectrum exhibits less than 7 dB power fluctuations between 1450 nm and 1650 nm. It is theoretically found that the flat SC is mainly generated by the effect of self-phase modulation. These obtained results show the further potential applications of CNT-technologies in optical communications.

Chapter 8 Conclusions and Future Works

8.1 Conclusions

In summary, this thesis focuses on the investigation of carbon-nanotube-based saturable absorbers in passively mode-locked fiber laser applications in order to achieve good performance of the whole laser system. The research mainly involves three subjects including the design and fabrication of CNT-based devices, the investigation of passively-mode-locked fiber lasers by using CNT-SAs; and the application of the CNT-SAs embedded mode-locked fiber lasers.

Different methodologies of CNT deposition to obtain good performance CNT-SAs have been investigated. They include spray-coating, optically-driven deposition, chemical vapor deposition of vertically-aligned CNTs. The main achievements in terms of the passively mode-locked fiber laser applications utilizing the fabricated CNT-SAs are summarized as follows.

(1) On the subject of improving the performance of existing CNT-SAs, we focus on enhancing the thermal damage threshold of CNT-SAs in which CNTs are integrated on optical fibers to establish light-CNT interaction. The scheme of evanescent-field interaction with CNTs is explored rather than the direct interaction. Since only a portion of light interacts with CNTs, the optical absorption-induced heating on CNTs is deferred to a higher intensity of the incident light. Three kinds of fibers are employed to construct CNT-SAs including tapered fibers, side-polished fibers, and standard SMFs.

- a) An improvement on the uniform distribution of CNTs along the tapered fibers is made compared to similar reports using optically-driven deposition method. We numerically optimize the taper waist of tapered fibers to be $\sim 9 \mu\text{m}$. Experimentally, we prepare the adiabatically tapered fiber with the taper waist of $\sim 9 \mu\text{m}$ by heating the standard SMF using a flame together with mechanical pulling. Subsequently, CNTs are deposited around the sidewall of tapered fibers by optically-driven deposition method. By carefully preparing the CNT solution as well as controlling the incident power and duration, Such CNT-deposited tapered fibers can ensure a long interaction distance of $\sim 6.6 \text{ mm}$. However, the total insertion loss of CNT-deposited tapered fiber is around $\sim 6 \text{ dB}$, which requires high pump power in laser application.
- b) For the first time, the deposition of CNTs onto side-polished fibers by optically driven deposition method is experimentally demonstrated. We numerically optimize the polished depth of the side-polished fiber to be $\sim 57.2 \mu\text{m}$ in order to achieve efficient light-CNT interaction. Experimentally, by controlling the incident power and deposition time, a reasonable insertion loss of $\sim 1\text{-}2 \text{ dB}$ can be achieved after CNT deposition. The prepared CNT-deposited side-polished fiber has shown the thermal damage threshold of $\sim 58 \text{ mW}$ that is higher than that of the conventional CNT-SAs around 30 mW . As the symmetrical geometry of the fiber is destroyed, light absorption along CNT-deposited side-polished fiber is polarization dependent. Such CNT-deposited side-polished fiber can assist the

constructed fiber laser to produce high-energy pulses of ~ 81.3 nJ in the Q-switching operation and multiple types of pulses in the mode-locking operation.

- c) A novel scheme of fiber-end-type CNT-SAs in which CNTs are deposited on fiber end of standard SMF in a ring pattern is proposed and demonstrated. We numerically optimize the inner ring diameter of CNTs in the range of 9-15 μm for an efficient evanescent-field interaction as well as minimize the optical absorption-induced heating. Experimentally, we deposit CNTs on fiber end in ring pattern by optically-driven deposition method. By controlling the incident power and deposition duration, various inner ring diameters of CNTs can be achieved. The results show that the thermal damage threshold of CNT-SA with the inner ring diameter of ~ 10 μm is increased by around 130% compared with an evenly deposited one. An all-fiber Fabry-Perot laser is further developed to investigate the performance and the thermal damage threshold of CNTs. The laser could produce pulses with the pulse energy up to 114 nJ in Q-switching regime which is higher than the peer reports utilizing CNT-SAs. When operating in mode-locking state, the laser could generate pulses with repetition rate of ~ 211.84 MHz and pulse width of ~ 680 fs. The mode-locked laser with an intra-cavity power higher than 30 mW is further investigated for a 12-hour continuous operation. The stable operation demonstrates that the proposed CNT-SA can withstand a relatively high optical power without significant performance degradation. Furthermore, benefiting from the evanescent-field interaction in the proposed CNT that enables mode-locked laser to operate at the relatively high intra-cavity power, we have demonstrated bound states of soliton with a high

fundamental repetition rate from CNT-based mode-locked fiber laser for the first time.

- d) Beside the optically-driven deposition method, we have demonstrated the possibility of direct growth of VACNTs with controllable tube diameter on a side-polished fiber by using various chemical vapor deposition methods. The scanning electron microscopy images and Raman spectrum are characterized confirming that VACNTs are successfully growth on optical fiber.

(2) On the subject of improving the performance of passively mode-locked fiber lasers, for the first time, the stability of dispersion-managed mode-locked fiber laser with near-zero net cavity dispersion is figured out to be relevant to the modulation depth of saturable absorber. Experimentally, we construct a dispersion-managed mode-locked fiber laser incorporating with CNT-SAs with different modulation depths. It is observed that there is an unstable region around net zero cavity dispersion where the laser only produces random pulse bursts instead of stable pulse trains. By the implantation of CNT-SAs with modulation depth increasing from 6.4% to 12.5%, such unstable region can be shrunk by 31.3%. Numerical studies are also performed to investigate the influence of SAs on the stability of mode-locked fiber laser with near-zero net cavity dispersion. It is found that the instability of laser with near-zero net cavity dispersion is originated from the strong spectral filtering due to finite gain bandwidth. In order to balance the filter loss, a SA with large modulation depth is necessary. The obtained results are not merely applicable to the dispersion-managed mode-locked fiber laser incorporating CNT-SAs, but also could be a general guidance for the laser using similar kinds of SAs.

(3) On the subject of the application of dispersion-managed mode-locked fiber lasers, we demonstrate the flat supercontinuum generation by a 1.55- μm dispersion-managed mode-locked fiber laser incorporating CNT-SA and a normal dispersion highly nonlinear photonic crystal fiber for the first time. The CNT-based mode-locked fiber laser with the net cavity dispersion of -0.016 ps^2 produces pulse trains with the timing jitter as low as $\sim 35 \text{ fs}$ and the pulse width of around 620 fs . The pulse is amplified to achieve a high peak power and subsequently launched into the photonic crystal fiber. Since the pulses propagate in the normal dispersion regime of the PCF, linear frequency chirp is induced by self-phase modulation, which leads to a flat SC. A supercontinuum covering 200 nm with less than 7-dB power fluctuation is achieved, which has the potential application in optical communication and frequency metrology.

8.2 Future Works

The achievements in this research project present various solutions to the problems of existing CNT-SAs, and reach to the optimized design of passively mode-locked fiber lasers by figuring out the originality of the laser instability. The findings are expected to enrich the knowledge in the field of mode-locked lasers. The studies also suggest a number interesting research subjects which can lead to future studies.

The ring pattern of CNT-layer deposition on fiber end for CNT-SAs can be expanded to various fibers as well as different kinds of nano-materials. The merits of such scheme are the compact device with enhanced thermal damage threshold. For instance, CNTs can be deposited onto the end-facet of gain fibers in ring pattern, which could benefit mode-locked fiber lasers to shorten greatly the cavity length for the high-repetition-rate

pulse train generation [52]. In our research project, we only demonstrate the 1.55- μm mode-locked fiber laser incorporating CNT-SA with ring pattern. Generally, the CNT-SA with ring pattern can be applied in 1- μm , 1.3- μm , and 2- μm mode-locked fiber lasers provided that the tube diameters are properly selected. Additionally, the scheme is also applicable to graphene or the mixture of graphene and CNTs that is able to construct SAs with the broadband operation bandwidth and the relatively high thermal damage threshold.

The integration of vertically-aligned single-walled CNT array on optical fibers is an attractive way to achieve CNT-based devices with good performance. We have demonstrated the direct growth of VACNTs with tube diameter of 10 μm on side-polished fibers by using thermal CVD method. However, the synthesized CNTs are still multi-walled. Previous reports show that the tube diameter is linearly proportional to growth temperature [134]. Perhaps, the direct synthesis of single-walled VACNTs on optical fiber can be achieved by precisely controlling the growth temperature during thermal CVD in the near future.

Dispersion-managed mode-locked fiber lasers with near-zero net cavity dispersion in Fabry-Perot linear-cavity configuration can be an attractive design to generate excellent pulse trains in terms of high repetition rate, low timing jitter, large spectral bandwidth, and ultrashort pulse width. Our numerical studies show that the stretched pulses exhibit similar performance even if the cavity geometry is greatly scaled down. The shortened cavity length could benefit the mode-locked fiber laser for high repetition rate. When the net cavity dispersion is well designed and SAs are properly selected, the pulses with

large spectrum bandwidth as well as low timing jitter can be produced simultaneously from the laser. The major challenges in practical applications are how to scale down the cavity geometry without the scarification of cavity gain. Therefore, the highly earth-element doped fibers as gain medium are necessary to provide the sufficient gain. However, the group velocity dispersion of the gain fiber could be influenced due to the material doping. One alternative solution of gain fiber could be photonic crystal fibers whose group velocity dispersion can be tailored to balance the material dispersion and the resultant net cavity dispersion can be maintained.

Author's Publications

Journal Publications

- [1]. **H. H. Liu** and K. K. Chow, "Dark pulse generation in fiber lasers incorporating carbon nanotubes," *Optics Express*, accepted, 2014.
- [2]. **H. H. Liu** and K. K. Chow, "Operation-switchable bidirectional pulsed fiber laser incorporating carbon-nanotube-based saturable absorber," *Journal of Selected Topics in Quantum Electronics*, vol. 20, no. 5, pp. 0901905-1-0901905-5, 2014.
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Conference Publications

- [1]. **H. H. Liu**, Y. Yang and K. K. Chow, "A Low-Loss Carbon-Nanotube-Based Linear Cavity Fiber Laser for High Energy Pulse Generation," in *Conference on Lasers and Electro-Optics (CLEO) 2013*, paper CM11.5, San Jose, USA, Jun. 2013.
- [2]. **H. H. Liu** and K. K. Chow, "Optically-driven deposition of carbon nanotubes on erbium-doped fibers for short-cavity passively mode-locked fiber lasers," in *Photonics Global Conference (PGC) 2012*, paper 6458112, Singapore, Dec. 2012.
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Appendix

Appendix A

This appendix is included to calculate numerically the transmission (T) of side-polished fiber as a relationship of the polished depth when the polished fiber is coated by CNTs.

For a side-polished fiber, a part of cladding is removed which leads to an asymmetric geometry of fiber. Provided that the polished depth (d_p) is large, *i.e.* the polished sidewall is very close to core region, light confined in the core region will be influenced by the external medium. If the refractive index (n_{ex}) of external medium is less than the effective RI ($n_{eff} = \beta/k_0$) of the guided mode in fiber, the presence of external media only affects the propagation constant (β) of guide mode. On the contrary, if $n_{ex} \geq n_{eff}$, the power confined in core region is radiated into external medium in the direction of $\cos^{-1}(n_{ex}/n_{eff})$, which attenuates the transmitted power. In this case, a theoretical model concerning the mode-coupling between the guided mode of SMF and the radiation mode of external medium can be explored to derive the attenuation coefficient (α) of the side-polished fiber [88]. Due To the high refractive index of CNTs ($n_{ex} \approx 2.1$), the CNT-deposited side-polished fiber is classified the leakage power case, and the attenuation coefficient is related to d_p and n_{ex} . Suppose that the refractive indexes of fiber core and cladding are n_{core} , and n_{clad} , respectively, and the related radius are r_{core} and r_{clad} , by

using the Eigen-equation described in section 3.2.1.4; n_{eff} of the fundamental mode can be determined, and the normalized frequency of unperturbed field is written as:

$$V = k_0 r_{core} \sqrt{(n_{core}^2 - n_{clad}^2)} \quad (A.1)$$

in which k_0 is wave number and expressed by:

$$k_0 = \frac{2\pi}{\lambda} \quad (A.2)$$

where λ is the wavelength of incident field. The normalized propagation constant B of the guided mode is given by:

$$B = \frac{n_{eff}^2 - n_{clad}^2}{n_{core}^2 - n_{clad}^2} \quad (A.3)$$

The normalized frequency of wave in the external media is written by:

$$V_{ex} = k_0 r_{core} \sqrt{(n_{ex}^2 - n_{clad}^2)} \quad (A.4)$$

Proposed by Leminger and Zengerle, the attenuation constant α is derived as [88]:

$$\begin{aligned} \alpha = & \frac{4\sqrt{2}}{r_{core}} \frac{1-B}{V} \sqrt{\Delta(1+2\Delta B)} \frac{V_{ex}^2 - BV^2}{V_{ex}^2 K_1^2(V\sqrt{B})} \\ & \times \int_0^1 \sqrt{1-\xi^2} \exp \left\{ -\frac{2V(r_{clad}-d_p)}{r_{core}} \sqrt{\left(\frac{V_{ex}^2}{V^2} - B\right)\xi^2 + r_{clad}^2} \right\} d\xi \end{aligned} \quad (A.5)$$

in which $K_1(x)$ is modified Bessel function of the second kind of first order, and Δ is the refractive index difference in the SMF written by .

$$\Delta = \frac{n_1 - n_2}{n_1} = \frac{n_{core} - n_{clad}}{n_{core}} \quad (A.6)$$

Once α is given, the transmission of CNT-deposited side-polished fiber with an interaction distance of L can be calculated by:

$$T = e^{-\alpha L} \quad (\text{A.7})$$

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