Chapter 1

Introduction

1.1 Harmonic mode-locked SOAFL

Mode-locked semiconductor amplifier based fiber lasers are possible candidates for high-bit-rate optical carriers in high-speed optical communication systems. It is known that harmonically mode-locking technology is one of the most intriguing methods for generating laser pulses with high repetition rate. However, in typical harmonically mode-locked fiber ring laser, maximum pulse repetition rate is limited by the bandwidth of intracavity $LiNbO_3$ Mach-Zehnder or electro-absorption intensity modulator. The requirement of a broadband optoelectronic or optical modulating components was relaxed by using rational harmonic mode-locking [1], or frequency multiplication with modulator nonlinearity techniques [2, 3]. More recently, pulses repetition frequency in FM mode-locked fiber lasers can be increased via a fiber Fabry-Perot filter (FFP) based wavelength selecting and filtering technique within the laser cavity [4]. Kamal K. Gupta *et al.* demonstrate pulse repetition frequency multiplication in AM mode-locked fiber ring lasers using optical filtering realized via intracavity FFP filter. However, in their experimental, the generated pulse train was obtained with repetition rate up to 3.477 GHz via a modulation signal of 869.28 MHz which corresponds to a rational harmonic order of only 4 [5]. M. W. K. *et al.*observed 40 GHz repetition rate optical train when the RF drive frequency of the modulator was ~10 GHz via a tunable FFP filter [6]. K. Zoiros *et al.* observed 8th-order rational harmonic mode-locking via an intracavity filter and 5 GHz DFB laser as seeding optical source [7]. However, none of the above authors generated high repetition rate up to 10 GHz or larger with modulation frequency f_m ~1 GHz via optically injection SOA-based fiber ring laser without any components, like FFP filter. In this letter, we demonstrate a simple technique for generating a 13 GHz pulse-train from a SOA-based fiber ring laser system by using optical pulse injection via a gain switching laser diode at repetition of 1 GHz. The rational harmonic mode-locking order of as high as 13 is achieved.

1.2 Backward Optical Injection Mode-Locking of SOAFL

Pulsed fiber optical sources with pulsewidth of some picoseconds and GHz repetition frequencies are of great interest in particular for the development of high speed optical communication systems. For experimental systems to be installed in the laboratory, the required sources are with wide tunability of wavelength, pulse width and repetition rate. Mode-locked semiconductor amplifier based lasers are possible candidates for optical carriers in high-speed optical communication systems. It is known that harmonically mode-locking technology is one of the most intriguing methods for generating pulses with high repetition rate. At frequencies of several tens of gigahertz, the low cost of electronics signal sources make optical techniques attractive for generating high repetition-rate optical pulses. Different approaches include multiplying the repetition-rate of a lower frequency optical pulse-train [8-10] or high-order mode-locking of a fiber ring laser [8, 9]. However, most of wavelength tunable short pulse generation techniques have used active mode locking of an erbium doped fiber ring laser with lithium niobate modulator and wavelength tunable filter.

Recently, a semiconductor fiber ring laser using a TWSOA has been attracted research interest due to its broad wavelength-tuning range, high stability, narrow linewidth, single-mode output capability, etc [10-13]. Various cavity configurations have recently been demonstrated to implement high-repetition-rate wavelength-tunable SOAFL. In particular, the generation of a tunable 40 GHz optical pulse-train from a fiber ring laser with a semiconductor optical amplifier has been developed by using 10 GHz electronics and optical repetition-rate multiplication. The wavelength of the 40 GHz pulse-train with pulsewidth of ~ 8 ps can be tuned by a tunable fiber Fabry-Perot (FFP) filter in the ring over a wavelength range of 20 nm [14]. Different approach has also been achieved by using a 5 GHz DFB laser as seeding optical source [15]. However, these schemes are more complicated and not cost-effective.

A hypothesis for the pulse repetition rate multiplication in actively modelocked lasers can be obtained by temporally considering the interaction between circulating pulses and the cavity loss modulation (see Fig. 1.1). If we consider the laser is modelocked at the Nth harmonic of its cavity fundamental mode frequency with N pulses circulating in the cavity, and the arrival time of each pulse with respect to loss minima is delayed by reducing the RF driving frequency. When the pulse arrival time is delayed by half of the modulation period T, it will pass through the loss maximum on its next arrival to the modulator, as shown in the top trace of Fig. 1.1.

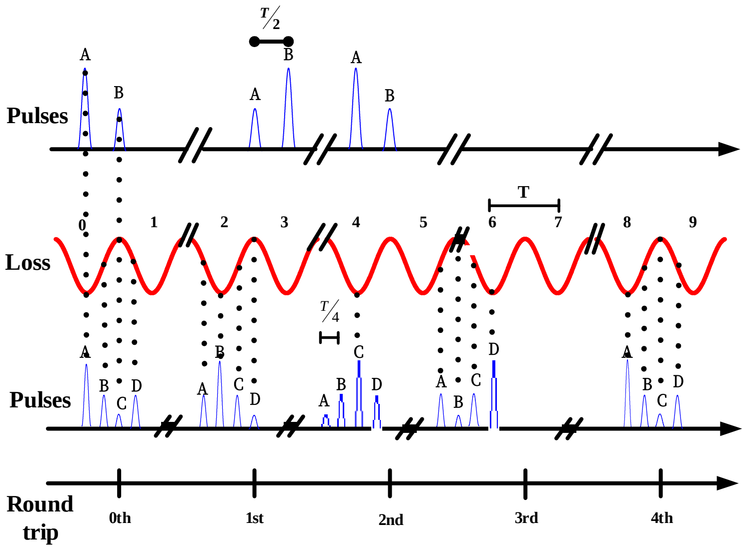

Fig. 1.1 Timing diagram of PRF doubling and tripling process when drive frequency is lower than frequency where shortest and most stable pulses are generated

However, complete quenching of this pulse does not occur since the gain medium relaxation time is much longer than the pulse period. After a further delay of *T*/2, the pulse will arrive at loss minima again receiving minimum loss and maximum gain. In order words each pulse will experience minimum loss in cavity every second round-trip time, which eventually double the repetition rate of the output pulses. Such a concept holds for higher frequency multiplication orders. Nonetheless, it can easily be noticed that in each round trip the pulse amplitude would fluctuate more frequently than in the frequency doubling case, hence more amplitude noise will be involved [16].

1.3 Femtosecond Mode-locked of SOAFL

Femtosecond mode-locked Erbium-doped fiber lasers (EDFLs) were comprehensively investigated by combining passively mode-locking and versatile pulse compressing schemes. Previously, a 98-fs pulse can be directly generated from passively mode-locked EDFL by incorporating an EDFA as a pulse compressor and a positive group velocity dispersion (GVD) fiber as a chirp compensater [17]. Alternatively, the pulse of a passively mode-locked EDFL with a polarization sensitive isolator can be shortened from 124 fs to 50 fs after adiabatic soliton narrowing and high-order soliton compression in a laser diode pumped nonlinear amplifying loop mirror (NALM) with 4m-long dispersion-shifted fiber [17]. Notably, a nonlinear olarization rotation scheme was employed to completely remove the continuous-wave component in a passively mode-locked EDFL pulse, which facilitates the shortening of pulsewidth from 136 fs to 52 fs after high-order soliton compression [18]. Complete adiabatic compression of EDFL pulse without spectral-modulation induced pedestal is permitted by adding a dispersion decreasing fiber-nonlinear amplifying loop mirror based intensity-dependent switching technique [19]. To date, similar technique were employed to generate pulses as short as 125 fs at peak energy of 0.5 nJ from a figure-8 fiber laser can [20]. In contrast, few results on femtosecond pulse compression of actively mode-locked fiber lasers were addressed [21-23]. The ultrashort C-band wavelength division-multiplexing pulsewidth of 250 fs repeated at 6.3 GHz was successfully achieved by spectrally filtering the chirp compensated supercontinuum spectrum of an actively mode-locked EDFL pulse [21]. The actively mode-locked EDFL pulse-train at 20 GHz has shown to be compressed from 1.8 ps to 172 fs with the use of a dispersion decreasing fiber (DDF) and EDF based external amplifying recompressor [22]. A nearly transform-limited 850-fs EDFL pulse-train at 40 GHz can simply be obtained with intra-cavity dispersion-shifted fiber (DSF) compressing technology [23]. Recently, the backward optical injection induced gain depletion modulation has also been proposed as an actively mode-locking technique for semiconductor optical amplifier fiber lasers (SOAFLs) [24-26]. The effects of modulation waveform and gain-depletion time on the build-up of harmonic mode-locking dynamics in the backward optical injected SOAFL were theoretically and experimentally elucidated [26]. To obtain the shortest mode-locking pulsewidth, a backward dark-optical comb injection induced optically harmonic mode-locking of a semiconductor optical amplifier (SOA) based fiber laser (referred as SOAFL) was primarily reported [27]. Nonetheless, the shortest pulsewidth ever generated from actively mode-locked SOAFLs were around 1 ps in view of previous reports [27-29]. In this article, we demonstrate for the first time the generation of high-order femtosecond soliton pulse from a backward dark-optical-comb injection-mode-locked SOAFL, which is achieved by using the fiber based linear dispersion compensation and nonlinear soliton compression techniques.

1.4 The Organization of Thesis

In chapter 2, we demonstrate the theory of dispersation compensation and soliton compression. The frequency chirp of SOAFL mode-locked pulses are negative and frequency decreases toward the trailing edge. It means the chirp parameter $C < 0$ and the instantaneous frequency increases linearly from the trailing edge to the leading edge. The DCF has large negative dispersion (dispersion parameter D) at 1.5 μm wavelength. It is in the normal-dispersion regime and $\beta_2 > 0$. Pulse compression is achieved, in this scheme by taking advantage of a non-linear phenomenon in optical fibers known as SPM. This nonlinear phenomenon is responsible for the spectral broadening of optical pulses in fibers, and will interact with GVD in the anomalous dispersion regime to produce optical solitons. In the case of a fundamental or first-order soliton, the effects of SPM cancel the effects of anomalous GVD perfectly, and the soliton propagates whilst preserving its sec h^2 shape in a loss less optical fiber.

In chapter 3, we demonstrate the harmonic mode-locking dynamics of a backward optical injection modulated SOAFL. The effects of gain-depletion time and modulation frequency on the mode-locked pulse shape and power have also been theoretically analyzed and experimentally demonstrated. The backward dark-optical combs modulation is much easier to initiate harmonic mode-locking in SOAFL than the bright-optical combs modulation. The effects of gain-depletion time and gain-recovery time on the build-up of the mode-locked SOAFL pulse-train are elucidated, and the dark-optical combs pulse-train are found to be extremely suitable for XGM induced mode-locking.

In chapter 4, we demonstrate femtosecond eighth-order soliton pulse generation from a backward dark-optical-comb injection mode-locked SOAFL after external compression in DCF and SMF. The backward injection of dark-optical-comb with duty-cycle >94% provides a cross-gain-modulation induced mode-locking of the SOAFL with a shortest pulsewidth of 15 ps ever reported at repetition frequency of 1 GHz. Theoretical simulation has been performed to obtain the optimized input power and fiber length for the external chirp compensating and pulse compressing stages. The pulsewidth and TBP of the chirp compensated SOAFL pulse become 8.6 ps and 0.48, respectively, after propagating through a 420 m-long DCF. By passing the chirp compensated SOAFL pulse through a 112m-long SMF, the eighth-order soliton pulse can be generated at input peak power of up to 51 W. The soliton-compressed SOAFL pulsewidth can further be shortened from 270 fs to 200 fs by propagating through a $\lambda/4$-wave plate and a linear polarizer, which greatly suppresses pedestal induced from the intensity dependent nonlinear PMD effect. As a result, the linewidth and TBP of the nonlinearly soliton compressed SOAFL pulse further increases to 13.8 nm ($\Delta\nu = 1.7$ THz) and reduces to 0.34.

1.5 References

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