Chapter 4
Generation of femtosecond pulse by soliton-effect compression of backward dark optical comb injection mode-locked semiconductor optical amplifier fiber laser

4.1 Introduction

By using an integrated electro-optic modulator based loss-modulation technique, the actively mode-locked erbium-doped fiber lasers (EDFLs) [1-3] with picosecond pulsewidth at ultra-high (10-40 GHz) repetition rates have emerged at an early stage. However, the EDFL can not be intrinic gain-modulated due to its nature of extremely long carrier lifetime (up to several ms). Later on the direct gain-modulation of semiconductor optical amplifier (SOA) via the periodical control on its of driving current has been employed as the main scheme for mode-locking the SOA based fiber-ring lasers (referred hereafter as SOAFLs) [4-6]. Recently, the backward optical injection is introduced as a novel optical cross-gain-modulation (OXGM) technology to achieve mode-locking in SOAFL [7-10]. Particularly, the comparison between sinusoidal-wave and pulsed injection induced XGM and mode-locking were done to explain the effect of the injecting waveform on the gain-depletion dynamics and the mode-locking performance of SOAFL. The established theoretical model suggests an optimized mode-locking under sufficiently large-duty-cycle and high-level injection [12], while the experiment was demonstrated that a backward injected signal with larger duty cycle is mandatory to optimize the mode-locking performance of the SOAFL [13]. 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 [14]. With the OXGM scheme, a fine adjustment on the waveform of backward injected optical signal, we have previously obtained the shortest mode-locked pulsewidth of 12 ps from the SOAFL at repetition frequency of 5 GHz by using a digital TTL-pattern externally modulated DFBLD [12]. Patrick et al. have ever obtained a pulsewidth of 8.4 ps at 10 GHz from the SOAFL system, which is externally injected by a harmonically mode-locked, 1543-nm external-cavity semiconductor laser at 10 GHz. To initiate a strong gain-depletion modulation, the average power of the pulse launched into the SOA is optically amplified to 10 dBm by using EDFA [7]. Similar experiment has also been implemented by gain-depleting the SOA with a gain-switched and pulse-compressed distributed-feedback laser diode (DFBLD) [8], which generate a mode-locked pulsewidth of 4.3 ps under such an OXGM configuration. It is realized that the SOA plays both the roles of gain medium and modulator in above works, while the mode-locking is initiated in the SOAFL by fast periodical gain-depleting and relatively slow gain-recovering the SOA under a strong pulse-injection. Mak, Tsang and Liu also reported a pulsewidth of 8 ps at 40 GHz from the OXGM mode-locked SOAFL [9]. The shortest pulsewidth ever generated from actively mode-locked SOAFLs is around 3.2 ps at repetition rate as high as 50 GHz [10]. More recently, the use of photonic-crystal fiber (PCF) based pulse compressor has shortened the pulsewidth to 176 fs and extended the wavelength to 1630 nm via Soliton self-frequency shift [11]. In this paper, we demonstrate for the first time the femtosecond soliton generation of an optical harmonic mode-locked SOAFL pulse at repetition of 10 GHz. The mode-locking is initiated by backward injection of dark-optical-comb pulse-train with a pulsewidth of 25 ps at repetition frequency of 10 GHz. The wavelength of the backward injected dark-optical-comb is adjusted to obtain a maximum gain-depletion depth for optimized mode-locking. To further shorten the SOAFL pulsewidth, the dispersion-compensating fiber based linear dispersion compensation and single-mode fiber based nonlinear soliton compression results are reported. The effects of input power and pulsewidth on the compressing output are investigated.

4.2 Experimental Setup

4.2.1 Compression System for SOAFL at 1 GHz

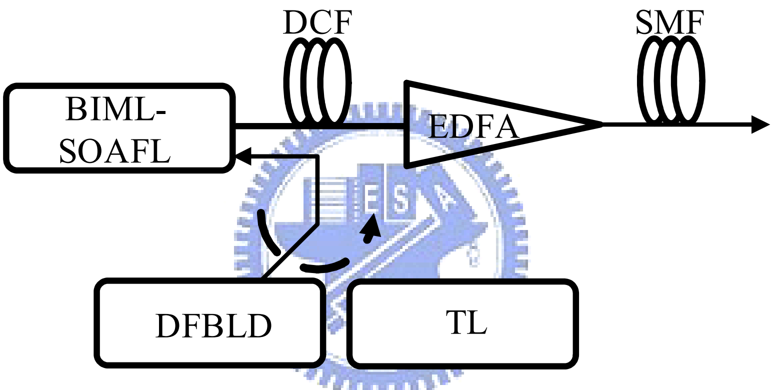


Fig. 4.2.1.1 The schematic diagram of the backward dark-optical-comb injection mode-locked SOAFL. DFBLD: distributed feedback laser diode; DCF: dispersion-compensating fiber; EDFA: erbium-doped fiber amplifier; SMF: single-mode fiber; TL: tunable laser

Figure 4.2.1.1 shows the schematic diagram of the backward dark-optical-comb injection mode-locked SOAFL. A butterfly-packaged distributed feedback laser diode (DFBLD, biased at 70 mA) operated at 1535 nm and 25^{o}C. The tunable laser is operated at 1550 nm and the output power is 6.42 mW. Subsequently, these pulses were compressed using a 420-m-long DCF (dispersion parameter D = -80 ps/km/nm) by compensating for the linearly chirp and the length of fiber is 420 m. To perform soliton effect compression, these pulses were then amplified by a high gain Erbium-Doped Fiber Amplifier (EDFA) and coupled into another 112m-long SMF (D = 20 ps/km/nm) to excite higher order solitons. The output pulse become narrower than the input pulse by a factor that increased with an increase in soliton order.

4.2.2. Compression System for SOAFL at 10 GHz

Figure 4.2.2.1 illustrates the backward-optical-injection mode-locked SOAFL (BIML-SOAFL) system with cavity length of 14 m.

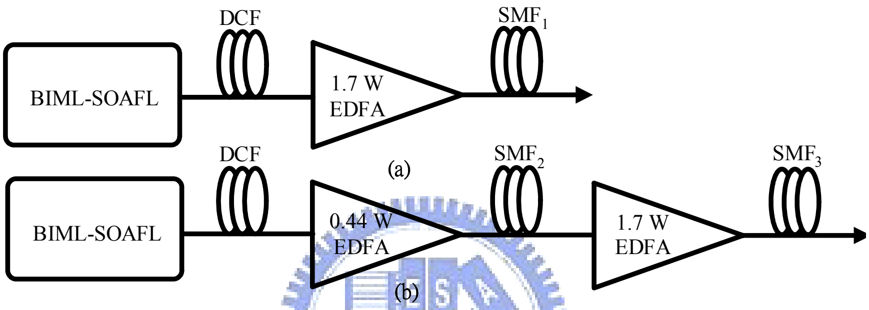


Fig. 4.2.2.1 The schematic diagram of the backward dark-optical-comb injection mode-locked SOAFL. DFBLD: distributed feedback laser diode; DCF: dispersion-compensating fiber; EDFA: erbium-doped fiber amplifier; SMF: single-mode fiber

Subsequently, the chirp of the output pulse was linearly compensated in a 75m-long dispersion-compensated fiber (DCF) with dispersion parameter of D_{DCF} = -80 ps/km/nm. Afterwards, the chirp compensated pulse was amplified and coupled in a SMF spool with D_{SMF} = 20 ps/km/nm to excite high-order soliton. In figure 4.2.2.1 (a), these pulses were coupled then amplified by a high gain 1.7 W Erbium-Doped Fiber Amplifier (EDFA) aninto another 80.6m-long SMF_1 (D = 20 ps/km/nm) to excite third order solitons. In figure 4.2.2.1 (b), these pulses were first amplified by a high gain 0.44 W Erbium-Doped Fiber Amplifier (EDFA) and coupled into another 257m-long SMF (D_{SMF} = 20 ps/km/nm) then amplified by a high gain

1.7 W Erbium-Doped Fiber Amplifier (EDFA) into another 17m-long SMF_3 (D = 20 ps/km/nm) to excite 1.7 order solitons.

4.3 Results and Discussion

4.3.1 200 fs SOAFL pulse at 1 GHz

Previously, the linearly and nonlinearly pulse-compressed SOAFL pulse shapes after passing through dispersion-compensating fiber (DCF) and single-mode fiber (SMF) are shown in Fig. 4.3.1.1.

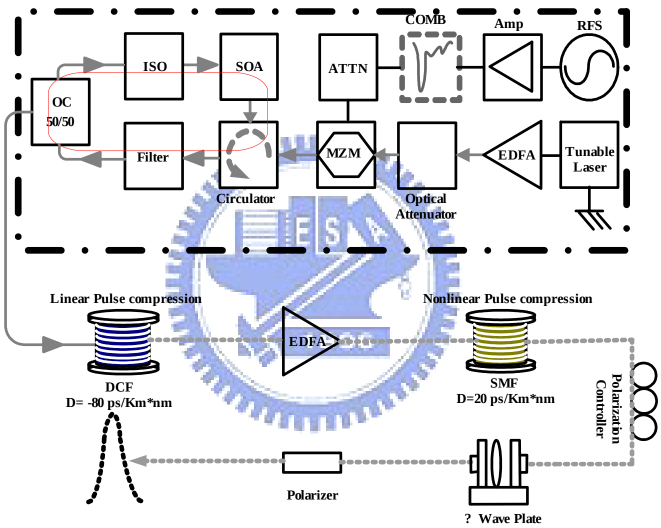


Fig. 4.3.1.1 The schematic diagram of the backward-optical- injection mode-locked SOAFL. ATT: attenuator;Amp: power amplifier; COMB: comb generator; EDFA: erbium-doped fiber amplifier; ISO: optical isolator; OC: optical coupler; SOA: semiconductor optical amplifier;RFS: RF synthesizer.

The linear dispersion compensation of the mode-locked SOAFL pulse is achieved with a 200m-long DCF, which results in a slightly compressed pulsewidth of 10.8 ps due to the large negative dispersion of the DCF (D~-80 ps/nm·km). In addition, the soliton-like pulse compression under the interaction between the group velocity dispersion (GVD) and the self-phase modulation (SPM) effects in the SMF has also been employed, which nonlinearly compresses the input SOAFL pulse with high peak-power. The pulse-compression can be constructed entirely by fiber segments with normal and anomalous GVD operating at soliton regime, [12] where the maximum pulse energy is theoretically limited to 100 pJ. At higher energy, wave-breaking occurs and is manifested as multiple-pulsing. To perform, additional EDFA is necessary in our case to enlarge the peak power of SOAFL pulse for high-order soliton generation. The SPM generates a frequency chirp such that the leading edge is red shifted and the trailing edge is blue-shifted from the central frequency. With the SPM-induced linewidth broadening effect, the finite gain-bandwidth limitation of the SOAFL can be released. Meanwhile, the anomalous GVD compensates such a frequency chirping at a certain propagation distance, resulting in a pulse compression over the central part of the SOAFL pulse. The pulsewidth of the mode-locked SOAFL can be nonlinearly compressed to 1.2 ps after propagating through a 5km-long SMF (D~16 ps/nm·km) as shown in Fig. 4.3.1.2.

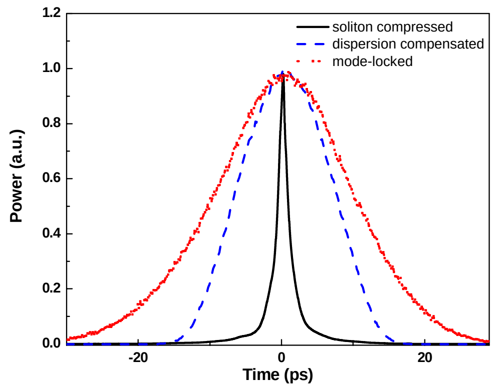


Fig. 4.3.1.2 Comparison of SOAFL pulse shapes after mode-locking (dotted curve), linear dispersion compression (dashed curve) and nonlinear soliton compression (solid curve).

The lasing spectra of the mode-locked SOAFL after propagating through the DCF and SMF are plotted in Fig. 4.3.1.3. The spectral linewidth and time-bandwidth product of the original mode-locked SOAFL pulse are 0.12 nm ($\Delta\nu$= 15 GHz) and 0.23, respectively. After propagating the amplified pulse through a 200m-long DCF, the pulsewidth, linewidth and time-bandwidth product become 10.8 ps, 0.12 nm ($\Delta\nu$= 15 GHz) and 0.16, respectively. However, a nonlinear compensating induced linewidth broadening happened due to a large input power of 92 mW at this stage, which is decreased by 3dB to remain output linewidth unchanged. The nonlinear soliton compression further increases the linewidth of the SOAFL pulse to 2.06 nm ($\Delta\nu$= 257.5 GHz), corresponding to a transform limited time-bandwidth product of 0.31.

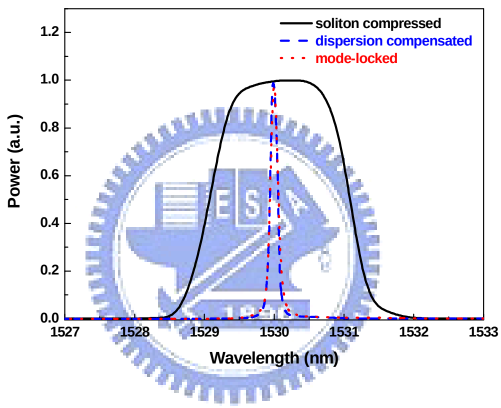


Fig. 4.3.1.3 Lasing spectra of dark-optical comb mode-locked SOAFL pulse before (dotted curve) and after propagating through a 200-m DCF (dashed curve) and a 5-km SMF (solid curve).

Originally, the mode-locked SOAFL pulses exhibit two orthogonally polarized components since the SOAFL ring cavity is not polarization-mode maintained. Due to the intensity-dependent nonlinear birefringence, the intense central peak and the weak pedestal with orthogonal polarization modes may experience different phase shifts during propagating in the SMF, which inevitably causes a pulse broadening (τ_{FWHM} = 2.3 ps) and separating phenomenon, as shown in Fig. 4.3.1.4. Such a pulse broadening can be overcome by adding an linear polarizer after the fiber pulse compressor, which has previously been employed by Ahmed *et al.* to demonstrate a

185-fs pedestal-free soliton compressed pulse from gain-switch laser diode system [13]. By rotating the polarization controller, the intense central peak can be fully compensated and changed to a linear polarization state while leaving the pedestal component in a different polarization state. Such an orthogonally polarized pedestal can subsequently be filtered by a linear polarizer, and the compressed SOAFL pulse shape (τ_{FWHM} = 1.8 ps) can be nearly pedestal-free after fine-adjusting the polarization controller. Finally, the tiny pedestal is completely eliminated by detuning the input power at the DCF compensating stage. This results in a shortest pulsewidth of 1.2 ps.

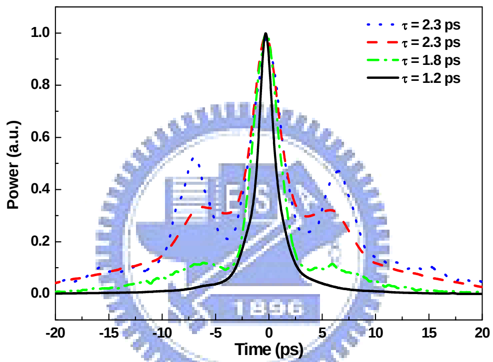
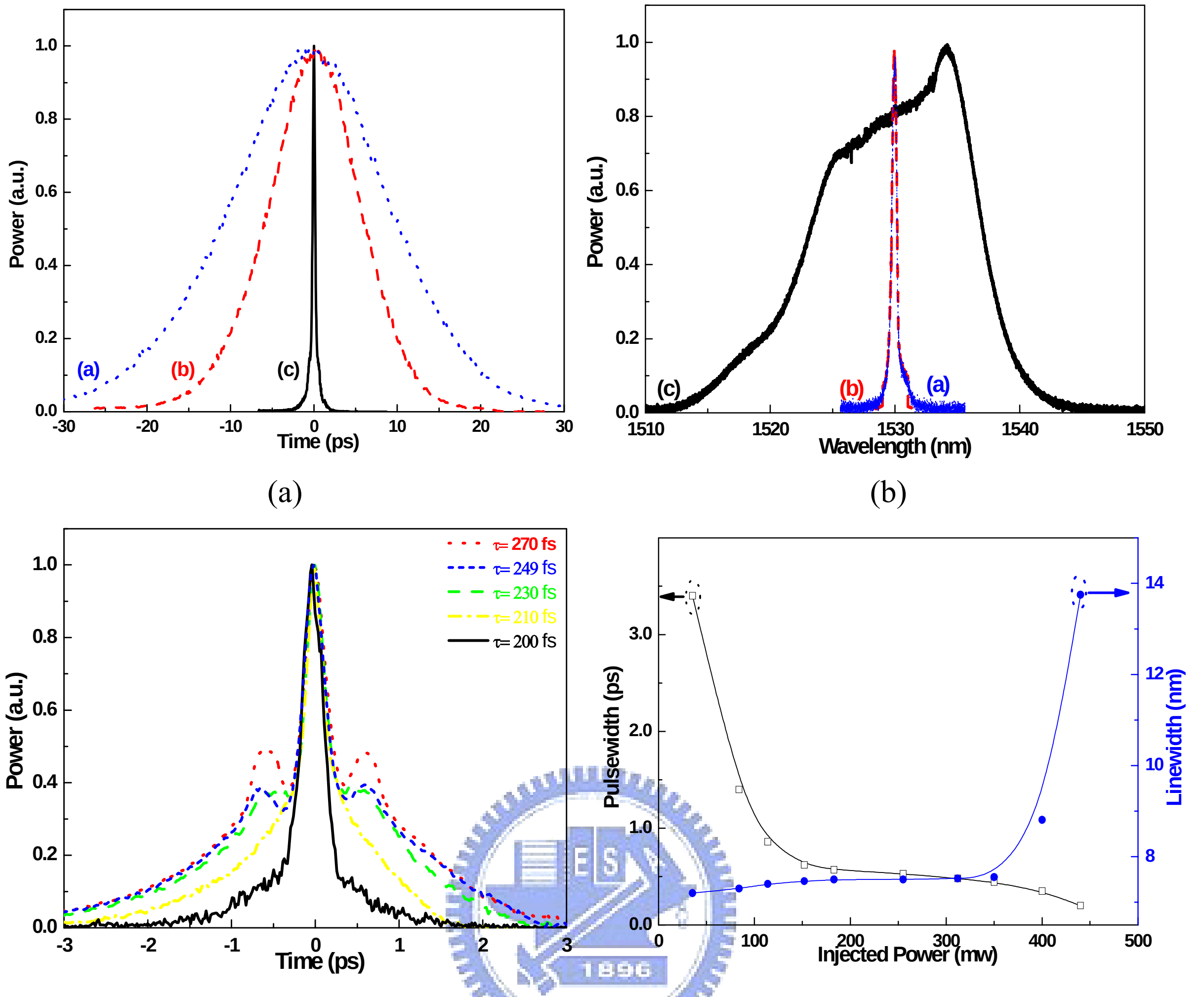


Fig. 4.3.1.4 The suppression of polarization-mode dispersion induced side-lobe in the auto-correlated trace of the backward optical-comb injection-mode-locked SOAFL pulse shapes. Dotted curve: the amplified mode-locked pulse shape after propagating through SMF. Dashed curve: partially controlled polarization mode by adjusting the polarization controller. Dash-dotted curve: nearly polarization mode dispersion free pulse shape. Solid curve: pedestal-free pulse shape via the fine adjustment of input power at DCF stage.

However, unlike an optical-fiber-based pulse compressor for gain-switched DFB laser pulses has been optimized to 800 fs using a systematic procedure based on the initial complete characterization of the laser pulses, followed by numerical simulations of the pulse propagation in different types of fiber to determine the required lengths for optimum compression [14]. Using both linear and nonlinear compression techniques, an optimum compression factor of 12 is achieved. We must optimum the length of fiber and increase the input power. The output pulse became narrower than the input pulse by a factor that increased with an increase in soliton order. In order to optimum compression condition, we analyzed the propagation of a chirped pulse in a dispersive fiber by assuming the optical output from the SOAFL to be with a Gaussian profile and linear chirping [15]. We found, at the first-order approximation, an explicit expression for the optimum compression condition as $D_{DCF}L = -\Delta t/\Delta\lambda$, where D_{DCF} = -80 ps/km/nm is the dispersion parameter of DCF in ps/km/nm, L is the fiber length, Δt is the FWHM of the input pulse, and $\Delta\lambda$ is the chirped spectral width. Hence, we conclude the dispersion can be compensated using 420m-long DCF since the $\Delta t/\Delta\lambda$ of 33.3 ps/nm is obtained from experimental results. The linewidth and time-bandwidth product (TBP) of the original SOAFL pulse are 0.45 nm ($\Delta\nu$ = 56 GHz) and 0.84, respectively. After propagating through a 420m-long DCF, the auto-correlated mode-locked pulse shape becomes purely Gaussian and the pulsewidth is compressed from 15 ps to 8.6 ps at the linearly DCF stage, as shown in Fig. 4.3.1.5(a). Figure 4.3.1.5(b) reveals that the DCF compensated pulse exhibits an unchanged linewidth and a reduced TBP of 0.48. The input power should remain as below 45 mW to avoid the Self-phase modulation induced spectral broadening at the DCF stage.

The dispersion compensated pulses is further amplified and the compressed via a nonlinear soliton pulse compression in a SMF spool. Under a $sech^2$ pulse shape with appropriate peak power, the optical soliton is a balanced result of the interaction between the group velocity dispersion (GVD) and the self-phase modulation (SPM) effects in SMF with anomalous dispersion. The finite gain-bandwidth limitation of the SOAFL pulse can thus be released by the SPM-induced linewidth broadening effect, and the SOAFL pulse is concurrently shortened by compensating the SPM induced residual frequency chirp with the anomalous GVD in SMF. In principle, the peak power of the input pulse required for obtaining the N^{th}-order soliton pulse was theoretically derived as $P_N = 3.11\ N^2\beta_2/\gamma\tau^2 = 3.11\ N^2 D_{SMF}\lambda^2/2\pi c\gamma\tau^2$, where λ is the input wavelength, c is the speed of light, $\tau = 8.6$ ps is the input pulsewidth, $\gamma = 1.3$ W^{-1} km^{-1} and $D \cong 20$ ps/km/nm at 1550 nm denote the nonlinearity coefficient and the dispersion parameter, respectively, for the SMF with a core diameter of 9.3 μm [16]. In our experiment, the maximum peak power of the DCF dispersion compensated SOAFL amplified by a booster EDFA is up to 51 W (corresponding to an average power of 440 mW at repetition frequency of 1 GHz), which is sufficiently to generate an eighth-order soliton in the SMF spool. However, it should be cautionary that the multiple-pulsing effect could manifest at extremely high pulse energies. The soliton theory indicates that the high-order soliton will follow a periodic evolution with its original pulse shape recurring at multiples of the soliton period Z_0 [15], which is given by $Z_0 = 0.332c\tau^2\pi^2/D_{SMF}\lambda^2$. In our case, the optimized fiber length to obtain the shortest compressed pulse for an eighth-order soliton is approximately equal to $0.072Z_0$ or 112 m [17], where the estimated soliton period (Z_0) is about 1.6 km at 1550 nm. As a result, the nonlinearly compressed soliton pulse shape and corresponding spectrum after passing through SMF are shown in Figs. 4.3.1.5(a) and 4.3.1.5(b), which exhibits a $Sech^2$-like pulsewidth and a spectral linewidth of 270 fs and 13.8 nm, respectively.



(a) (b)

(c) (d)

Fig. 4.3.1.5 (a)The pulse shapes and (b) the lasing spectra of the SOAFL after mode-locking, linear dispersion compensation and nonlinear soliton compression; (c) The polarization-mode-dispersion (PMD) suppressed SOAFL pulse shapes (dotted: without PMD, dashed: partially PMD controlled, dash-dotted: nearly PMD-free, solid: pedestal-free pulse). (d) The peak-power dependent pulsewidth and linewidth at the SMF compression stage.

Nonetheless, the soliton-effect compression is more pronounced at the central part than at the side-lobe of the linearly chirped SOAFL pulse, such an inherent drawback (requiring sufficiently high peak energy) inevitably leads to a broadened pedestal split from the compressed pulse, as seen in Fig. 4.3.1.5(c). In most cases, there is only 40% of the total energy confined within the central part of an eighth-order soliton even at an optimized propagation distance [17]. Fortunately, the intensity dependent polarization characteristic of the amplified SOAFL pulse in the

SMF spool intensity-dependent nonlinear birefringence, which results in an efficient discrimination between the high intensity peak and the low intensity pedestal [18], This offers an alternative way to further suppress the unwanted pedestal of the eighth-order soliton pulse after passing through the SMF spool of optimized length. Consequently, the high intensity peak and the low intensity pedestal with different polarization states at the fiber output can be orthogonally separated each other by passing through a λ/4-wave plate and a linear polarizer. The polarization-mode dispersion induced side-lobe in the auto-correlated trace of the backward optical-comb injection-mode-locked SOAFL pulse shape can be gradually suppressed via the fine tune of the linear polarizer, as shown in Fig. 4.3.1.5(c). The pedestal-free pulse is eventually narrowing to 200 fs, which becomes comparable with those ever reported for a gain-switch laser diode system. The compressed pulsewidth and linewidth curves indicates a two-stage soliton pulse compressing phenomenon. The SOAFL pulsewidth is significantly compressed from 8.6 ps to 0.5 ps as the input peak power enlarges to 150 mW, however, the SPM effect is yet not sufficiently large to broaden the lasing spectrum, as shown in Fig. 4.3.1.5(d). This restricts the TBP of the compressed pulse (ranging between 3.1 and 0.58) approaching the transform limit of 0.31. The SPM and GVD is completely balanced when the input peak power increases to 400 mW or larger, wherein the pulsewidth and linewidth of the compressed SOAFL pulse abruptly shortens to 200 fs and broadens 13.8 nm ($\Delta\nu = 1.7$ THz), providing a nearly transform-limit TBP of 0.34. To date, this is already the shortest pulse ever reported for the actively harmonic mode-locked EDFLs or SOAFLs using either loss or gain modulation schemes.

Guy *et al.* have also reported a novel 10-GHz actively mode-locked laser operating at 1.3 μm, in which a discrete semiconductor laser amplifier serves only as a gain medium with an electro-absorption amplitude modulator based mode-locker.

Such a SOAFL has also generated a nearly transform-limited pulsewidth as short as 1.9 ps [4]. On the other hand, Kim *et al*. have ever observed the compression from 18.4 ps to 6.8 ps after passing through a 2-km SMF, which exhibits the linewidth and time-bandwidth product of 0.5 nm and 0.44, respectively [5]. In comparison, our new scheme show a great potential in generating shorter pulses at higher repetition rates since the mode-locked laser pulsewidth is inversely proportional to the square root of repetition frequency [5]. With a soliton pulse-compression technique, the SOAFL has shown to exhibit the shortest and nearly transform-limited pulsewidth to date. Patrick has ever obtained a pulsewidth of 8.4 ps at 10 GHz from a similar system externally injected by a harmonically mode-locked external-cavity semiconductor laser at 10 GHz and 1543-nm. The injected pulse is optically amplified in a dual-stage 1480nm-pumped EDFA, which launches into the SOA at a mean optical power of 10 dBm [7]. A nearly transform-limited 4.3-ps pulse-train at 20 GHz over a 16-nm tuning range was also reported under the injection of the DCF compressed 15-ps pulses from a 10-GHz gain-switched DFBLD at 1548.5 nm [8]. With a fine adjustment on the waveform of backward injected optical signal, we have previously obtained the shortest mode-locked pulsewidth of 12 ps from the SOAFL at repetition frequency of 5 GHz by using a digital TTL-pattern externally modulated DFBLD [14].

4.3.2 180 fs SOAFL pulse at 1 GHz

Such an optically mode-locked SOAFL can provide picosecond pulses over a wide wavelength range of up to 30 nm due to its fast carrier depletion induced by ultrafast optical-injection modulation. The mode-locked pulse forms behind the externally injected dark-optical-comb when the gain of SOA recovers to exceed the cavity loss. A sufficiently high modulation depth for the SOA operating at medium gain regime is required, which results in a short temporal “window” with net gain and the mode-locking with minimized pulsewidth can be initiated. With a backward dark-optical-comb injection waveform shown in Fig. 4.3.2.1(a), the optimized mode-locking result of the SOAFL is illustrated in Fig. 4.3.2.1 (b).

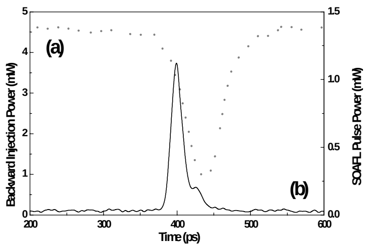


Fig. 4.3.2.1 Pulse shapes of the (a) injected dark-optical-comb and (b) mode-locked SOAFL.

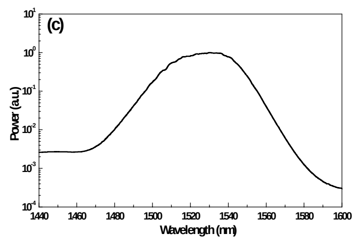
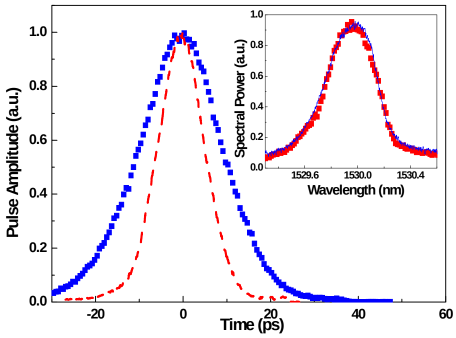


Fig. 4.3.2.2 (c) The amplified spontaneous emission spectrum of SOA operated at 15 ^{o}C.

At a repetition frequency of 1 GHz, the central wavelength, of the dark-optical-comb injection mode-locked SOAFL are tunable form 1530 to 1560 nm with spectral linewidth and average power of 0.45 nm and 0.1 mW, respectively. The mode-locked SOAFL pulsewidth are as large as 68 ps under the backward injection power of 1.3 mW, which significantly shortens to 15 ps as the backward injection power increases to 4.5 W. These results interpret that the fine adjustment on the SOA gain by precisely controlling the backward injection duty cycle and power are mandatory, since which helps to achieve both the larger modulation depth and the narrower gain window required for perfect mode-locking. The negatively chirped SOAFL pulse is dispersion compensated by passing it through a 420m-long DCF, however, it is observed that the pulse linewidth is nonlinearly broadened to 0.74 nm by the induced SPM effect at input power >90 mW. By attenuating the input power from 56 mW to <45 mW, the linewidth reduces from 0.52 nm ($\Delta\nu$ = 65 GHz) to 0.45 nm ($\Delta\gamma$ = 56 GHz), while the nonlinear spectral broadening effect is entirely released. Figure 3 reveals the unchanged spectrum of the DCF compensated pulse, which is coincident with that of the original mode-locked pulse. In comparison, Kim et al. have ever observed the compression from 18.4 ps to 6.8 ps after passing through a 2-km SMF, which exhibits the linewidth and time-bandwidth product (TBP) of 0.5 nm and 0.44, respectively. In our case, the auto-correlated mode-locked pulse shape becomes purely Gaussian, and the pulsewidth is compressed from 15 ps to 8.6 ps with a reduced TBP of 0.48 after propagating through a 420m-long DCF.

To perform the high-order nonlinear soliton compression, a booster EDFA is necessary in our case. The DCF compensated SOAFL pulse was further amplified to an average power of 440 mW at repetition frequency of 1 GHz (corresponding to a peak power of 51 W). From Eq. (2.3.3-1), it can be evaluated that such a peak power is sufficient to generate an eighth-order soliton ($N = 8$) in a SMF with D = 20 ps/km/nm at 1.55 μm. Since the soliton period for an 8.6ps pulse in the above-mentioned fiber was 1.551 km, the optimized fiber length to obtain the shortest eighth-order soliton compression would thus be 107.5 m (or equivalent to $0.072Z_0$ theoretically, where the estimated soliton period Z_0 is about 1.6 km at 1550 nm) in our case. As a result, the compressed pulse thus exhibits an extremely high intensity peak with low-intensity pedestal after propagating through the SMF with optimum length is shown in Fig. 4.3.2.4. It is found that even at an optimized propagation distance, there is only about 40% of the total energy confining within the central part of an eighth-order soliton pulse. Due to the intensity-dependent nonlinear birefringence, the high-intensity central peak and the low-intensity pedestal may experience different phase shifts and have different polarization states at the fiber output, which inevitably causes a pulse broadening to 216 fs associated with a separating phenomenon between the principle pulse and pedestals. Because the soliton compression is only effective at the central part of the pulse where the chirping is linear, a broad pedestal structure always appears around the compressed pulse.



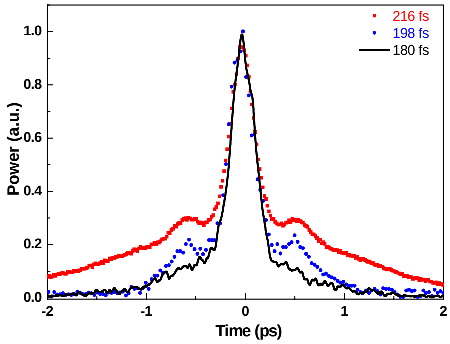


Fig. 4.3.2.3 Auto-correlated traces and lasing spectra of SOAFL pulse before and after chirp compensation.

Fig. 4.3.2.4 Original (dotted), partially birefringent filtered (dashed) and completely filtered (solid) soliton pulses

To completely suppress these pedestals, an intensity discrimination scheme that relies upon the intensity dependent polarization state of light in the fiber is utilized in our work. Originally, the mode-locked SOAFL pulses exhibit two orthogonally polarized components since the SOAFL ring cavity is not polarization-mode maintained. By rotating the wave plate at appropriate power levels, the phase shift of the central peak can be changed to a linear polarization state, while leaving the pedestal components in an orthogonal polarization state. Subsequently, such an orthogonally polarized pedestal is filtered by fine adjusting a linear polarizer behind the wave plate. The SOAFL pulse shape significantly changes to be pedestal-free, providing a shortening pulsewidth of 180 fs and a purified polarization state. The linewidth and time-bandwidth product of the eighth-order SOAFL soliton pulse become 13.8 nm ($\Delta\nu$=1.7 THz) and 0.31, respectively. The average power of the SOAFL pulse after soliton compressing and birefringent filtering can be as high as 25.2 dBm, corresponding to a peak pulse power of 1 kW at repetition frequency of 1 GHz. The insertion loss during the soliton compression process is less than 3 dB. Afterwards, three SMF spools with different lengths are employed to investigate the tolerance of high-order soliton on the input peak power and SMF length. Under the same input peak power, the nonlinear pulse compression results such as the pulsewidth, the linewidth, and the TBP in different SMF spools are shown in Figs. 4.3.2.5 and 4.3.2.6. The total insertion loss for each SMF spool with FC/APC connecter is 1.2±0.2 dB (the propagation loss of the Corning SMF is 0.2 dB/km). The soliton compressed pulsewidth measured at the output ends of three SMF spools with different lengths are shown in Fig. 4.3.2.5. Increasing the fiber length may obtain a similar spectral response with a larger dip at the central part, which is attributed to a larger phase change caused in the longer SMF. However, the SPM induced linewidth broadening effect is slightly unsymmetrical at both wavelength ends due to the finite gain response of the booster EDFA at shorter wavelength region, as shown in Fig. 4.3.2.5(a). At input power of 440 mW, the auto-correlation traces of the compressed pulses output from different-length SMF spools also reveal an increasing trend on the soliton pulsewidth, which elucidates a imperfect SPM-GVD balancing result for the soliton generated from longer SMF, as shown in Fig. 4.3.2.5(b). From these results, we conclude that the criterion on the fiber length for high-order soliton compression can be slightly released once the most crucial point of sufficient peak power is satisfied. Even though, the generation of transform-limited femtosecond soliton pulses from SOAFL could be greatly simplified by optimizing the SMF length to a theoretical value and meeting the peak power requirement. It is found in Fig. 4.3.2.5 that the pulse inevitably broadens as the SMF lengthens, while the residual chirp of SOAFL pulse is not fully compensated. Furthermore, the linewidth analysis also reveals an insufficient SPM effect happened in the SMF spool with longer length, which therefore leads to an enlarged TBP at the same input power, as shown in Fig. 4.3.2.6.

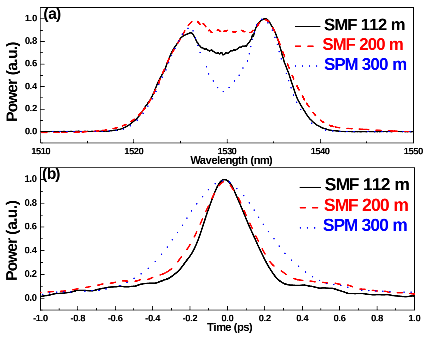


Fig. 4.3.2.5 Comparison on the pulsewidth and linewidth of the eighth-order soliton pulses compressed by SMF with different lengths.

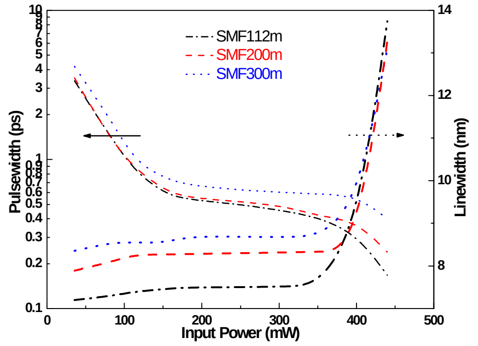


Fig. 4.3.2.6 Pulsewidth and linewidth of nonlinear compressed SOAFL pulse at different input powers and SMF lengths.

For wavelength tuning, the operating temperature of the SOA is setting at between 15°C and 35°C. This makes the gain peak of the SOA red-shifts from 1530 to 1560 nm. By setting the backward injection wavelengths at 1535 nm, 1549 nm, and 1565 nm, the optimized mode-locking of the SOAFL at wavelengths of 1530 nm, 1545 nm, and 1560 nm. can be achieved. At chirp compensating stage, the DCF lengths for the SOAFL at different wavelengths remain the same since the pulsewidth and linewidth of the SOAFL keep almost constant at all conditions. At nonlinear compressing stage, the estimated soliton order slightly changes from 7.8 to 8 as the central wavelength of the SOAFL red-shifts from 1530 to 1560 nm, however, the deviation in the optimized SMF length is within 10 cm. As a result, the nonlinear compressed pulsewidth and linewidth of the SOAFL are 190±10 fs and 13.7±0.1 nm, respectively. Note that a decreasing trend for the soliton pulsewidth at longer wavelengths is observed due to the slightly increased soliton order. Nevertheless, the TBP of the eighth-order SOAFL soliton at different wavelengths are controlled at 0.31~0.34. As the central wavelength detunes beyond 1530-1560 nm, the amplified peak power dramatically is decayed due to the finite gain bandwidth of the booster EDFA, which inevitably leads to the mismatch between the input peak power and the

SMF length for eighth-order soliton. The soliton compression thus becomes incomplete due to the overestimating length of the SMF at the nonlinear soliton compression stage.

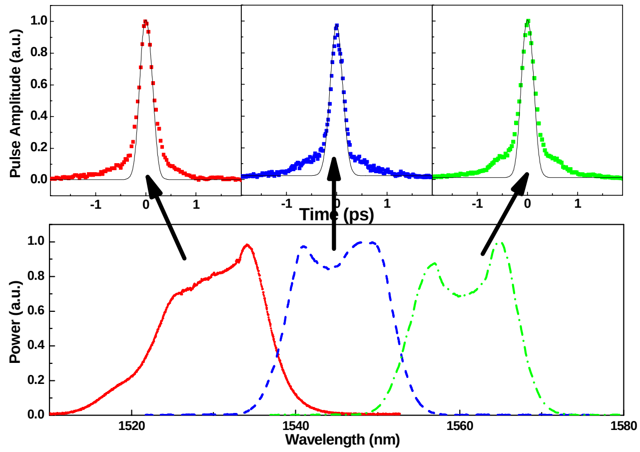


Fig. 4.3.2.7 The nonlinearly compressed pulse shapes and associated spectra at different SOAFL wavelengths.

4.3.3 620 fs SOAFL pulse at 10 GHz

Figure 3 shows the compressing configurations for the SOAFLs. Subsequently, the chirp of the output SOAFL pulse was linearly compensated in a 75m-long dispersion-compensated fiber (DCF) with dispersion parameter of D_{DCF} = -80 ps/km/nm. Afterwards, the chirp compensated pulse was amplified and coupled in a SMF spool with D_{SMF} = 20 ps/km/nm to excite high-order soliton. In figure 4.3.3.1 (a), these pulses were coupled then amplified by a 1.7 W booster EDFA into another 76.7m-long SMF (D = 20 ps/km/nm) to excite third order solitons. In figure 4.3.3.1 (b), these pulses were first amplified by a 0.44 W high-gain EDFA and coupled into a 257m-long SMF, and then amplified by a 1.7 W EDFA for a secondary 1.7-order soliton compression in another 17m-long SMF. By using the relationship of peak power and average power for P_{peak}~$P_{average}$/frequency·pulsewidth. When the RF synthesizer is operated at 10 GHz, we will not get higher order soliton than 1 GHz. So the pulsewidth of 10 GHz is not as narrow as 1GHz.

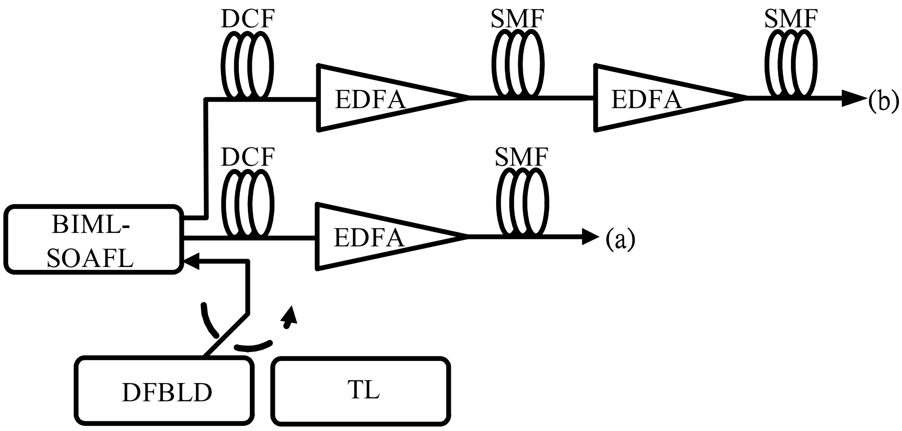
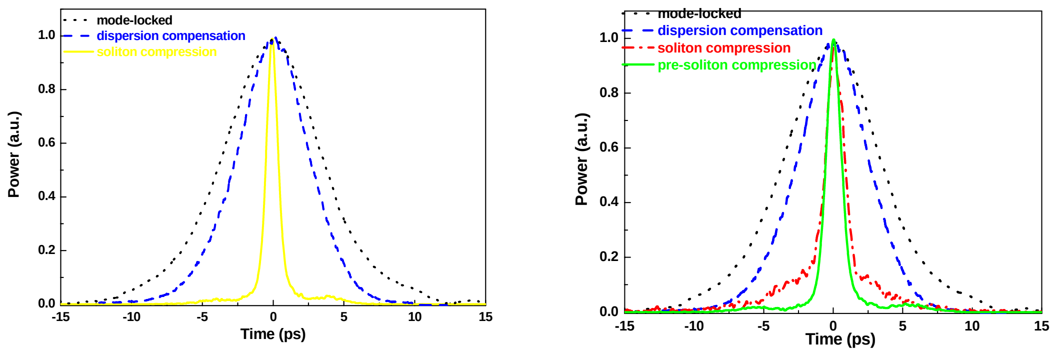


Fig. 4.3.3.1 The schematic diagram of the backward dark-optical-comb injection mode-locked SOAFL. DFBLD: distributed feedback laser diode; DCF: dispersion-compensating fiber; EDFA: erbium-doped fiber amplifier; SMF: single-mode fiber; TL: tunable laser

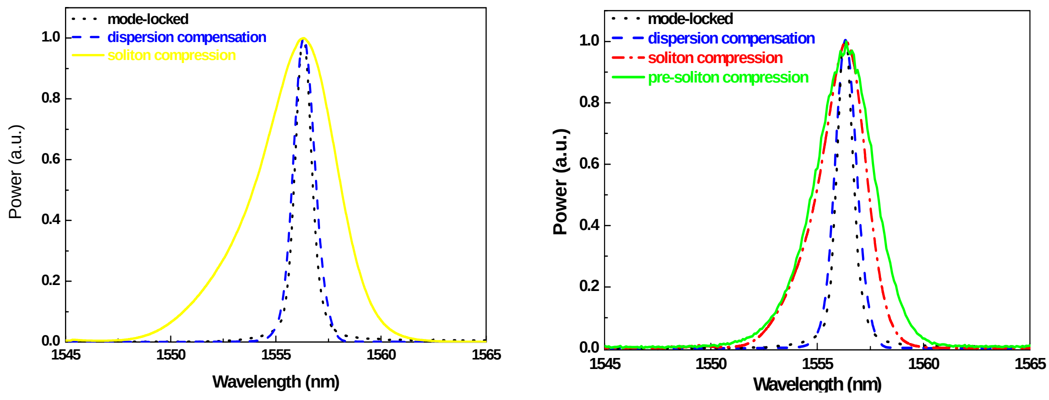
In this experiment the shortest pulsewidth at repetition frequency of 10 GHz ever reported in similar systems before pulse compressing. Later on, a DCF spool is employed to compensate the negative chirp of the mode-locked SOAFL pulse. An explicit expression for the optimum compression condition under the first-order approximation is described as $D_{DCF}L = -\Delta t/\Delta\lambda$ [15], where D_{DCF} = -80 ps/km/nm is the dispersion parameter of DCF in ps/km/nm, L is the fiber length, Δt is the FWHM of the input pulse, and Δλ is the chirped spectral width. Hence, we conclude the dispersion can be compensated using 75m-long DCF since the Δt/Δλ of 6 ps/nm is obtained from experimental results. The linewidth and time-bandwidth product (TBP) of the original SOAFL pulse are 0.9 nm (Δν = 112.5 GHz) and 0.61, respectively. After propagating through a 75m-long DCF, the auto-correlated mode-locked pulse shape becomes purely Gaussian and the pulsewidth is compressed from 5.4 ps to 4 ps at the linearly DCF stage, as shown in Fig. 4.3.3.2.



(a) (b)

Fig. 4.3.3.2 Comparison of SOAFL pulse shapes after mode-locking (dotted curve), linear dispersion compression (dashed curve) and (a) 80.6m-SMF_1 (solid curve), (b) 257m-SMF_2 (Dash-dotted curve), 17m-SMF_3 (solid curve).

Figure 4.3.3.3 reveals that the DCF compensated pulse exhibits an unchanged linewidth and a reduced TBP of 0.45. The input power should remain as below 45 mW to avoid the Self-phase modulation induced spectral broadening at the DCF stage. The dispersion compensated pulses is further amplified and the compressed via a nonlinear soliton pulse compression in a SMF spool. Under a $sech^2$ pulse shape with appropriate peak power, the optical soliton is a balanced result of the interaction between the group velocity dispersion (GVD) and the self-phase modulation (SPM) effects in SMF with anomalous dispersion. The finite gain-bandwidth limitation of the SOAFL pulse can thus be released by the SPM-induced linewidth broadening effect, and the SOAFL pulse is concurrently shortened by compensating the SPM induced residual frequency chirp with the anomalous GVD in SMF. In principle, the peak power of the input pulse required for obtaining the N^{th}-order soliton pulse was theoretically derived as $P_N = 3.11\ N^2\beta_2/\gamma\tau^2 = 3.11\ N^2 D_{SMF}\lambda^2/2\pi c\gamma\tau^2$, where λ is the input wavelength, c is the speed of light, $\tau = 4$ ps is the input pulsewidth, $\gamma = 1.3\ W^{-1}\ km^{-1}$ and $D \cong 20$ ps/km/nm at 1550 nm denote the nonlinearity coefficient and the dispersion parameter, respectively, for the SMF with a core diameter of 9.3 μm [16].



(a) (b)

Figure 4.3.3.3 Lasing spectra of dark-optical comb mode-locked SOAFL pulse before (dotted curve) and after propagating through a 75-m DCF (dashed curve) and (a) 80.6m-SMF_1 (solid curve), (b) 257m-SMF_2 (Dash-dotted curve), 17m-SMF_3 (solid curve)

In Figure 4.3.3.2(a) and Figure 4.3.3.3(a) , the maximum peak power of the DCF dispersion compensated SOAFL amplified by a booster EDFA is up to 42.5 W (corresponding to an average power of 1.7 W at repetition frequency of 10 GHz), which is sufficiently to generate an third-order soliton in the SMF spool. However, it should be cautionary that the multiple-pulsing effect could manifest at extremely high pulse energies. The soliton theory indicates that the high-order soliton will follow a periodic evolution with its original pulse shape recurring at multiples of the soliton period Z_0 [15], which is given by $Z_0 = 0.332c\tau^2\pi^2/D_{SMF}\lambda^2$. In our case, the optimized fiber length to obtain the shortest compressed pulse for an second-order soliton is approximately equal to $0.245Z_0$ or 80.6 m [17], where the estimated soliton period (Z_0) is about 329 m at 1556 nm. As a result, the nonlinearly compressed soliton pulse shape and corresponding spectrum after passing through SMF are shown in Figure 4.3.3.2 and Figure 4.3.3.3, which exhibits a Sech^2-like pulsewidth and a spectral linewidth of 762 fs and 4.2 nm, respectively.

In Figure 4.3.3.2(b) and Figure 4.3.3.3(b) , the maximum peak power of the DCF dispersion compensated SOAFL amplified by a booster EDFA is up to 11 W (corresponding to an average power of 0.44 W at repetition frequency of 10 GHz), than injected into 257m-long SMF. Upon increasing the EDFA output power to 42.5 W (corresponding to an average power of 1.7 W at repetition frequency of 10 GHz), the pulses reached the point of second optimal narrowing to 762 fs. Nonetheless, the soliton-effect compression is more pronounced at the central part than at the side-lobe of the linearly chirped SOAFL pulse, such an inherent drawback (requiring sufficiently high peak energy) inevitably leads to a broadened pedestal split from the compressed pulse, as seen in Fig. 4.3.3.4. In most cases, there is only 80% of the total energy confined within the central part of an third-order soliton even at an optimized propagation distance [17]. Fortunately, the intensity dependent polarization characteristic of the amplified SOAFL pulse in the SMF spool intensity-dependent nonlinear birefringence, which results in an efficient discrimination between the high intensity peak and the low intensity pedestal [16], This offers an alternative way to further suppress the unwanted pedestal of the third-order soliton pulse after passing through the SMF spool of optimized length. Consequently, the high intensity peak and the low intensity pedestal with different polarization states at the fiber output can be orthogonally separated each other by passing through a $\lambda/4$-wave plate and a linear polarizer. The polarization-mode dispersion induced side-lobe in the auto-correlated trace of the backward optical-comb injection-mode-locked SOAFL pulse shape can be gradually suppressed via the fine tune of the linear polarizer, as shown in Fig. 4.3.3.4.

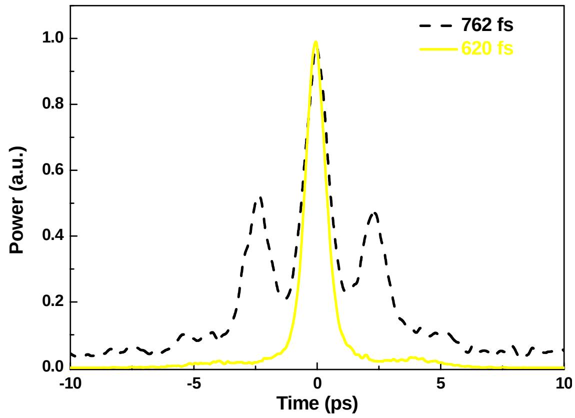


Fig. 4.3.3.4 The suppression of polarization-mode dispersion induced side-lobe in the auto-correlated trace of the backward optical-comb injection-mode-locked SOAFL pulse shapes. Dashed curve: partially controlled polarization mode by adjusting the polarization controller. Solid curve: pedestal-free pulse shape via the fine adjustment of input power at DCF stage.

The pedestal-free pulse is eventually narrowing to 620 fs, which becomes comparable with those ever reported for a gain-switch laser diode system (with compressed pulsewidth of 185 fs) [16]. The compressed pulsewidth and linewidth curves indicates a two-stage soliton pulse compressing phenomenon. This restricts the TBP of the compressed pulse approaching the transform limit of 0.31. The SPM and GVD is completely balanced when the input peak power increases to 400 mW or larger, wherein the pulsewidth and linewidth of the compressed SOAFL pulse abruptly shortens to 620 fs and broadens 4.2 nm ($\Delta\nu$ = 525 GHz), providing a nearly transform-limit TBP of 0.33. To date, this is already the shortest pulse ever reported for the actively harmonic mode-locked EDFLs or SOAFLs using either loss or gain modulation schemes.

With the backward injection of the dark-optical comb, the central wavelength and output power of the harmonic mode-locked SOAFL are 1556 nm and 132.2 μW, respectively. The dark-optical comb injection-mode-locked SOAFL pulse shape is shown in Fig. 3.3.1.3. In principle, the mode-locking pulsewidth is directly proportional with $(g_0)^{1/4}/(\delta^2 \cdot f_m{}^2 \cdot \Delta\nu^2)^{1/4}$, where f_m denotes the modulation frequency, $\Delta\nu$ represents gain bandwidth of SOA, g_0 is single-pass integrated gain of SOA, and δ denotes the modulation depth. The mode-locking pulsewidth reaches its minimum when the modulation depth is sufficiently high. In contrast, the SOAFL mode-locked by backward injecting a bright-optical comb only shows a tiny pulse-train with an extremely large level of continuous-wave background. Such a worse mode-locking feature under backward injection of a bright-optical comb has previously been interpreted, as attributable to the insufficient gain-depletion of the SOA within one modulation period. When the SOA is gain-depleted by backward injection of a bright-optical comb, the gain of the SOA cannot be fully depleted and the SOA almost remains in the gain regime. This is due to the insufficient backward injected photon density by the bright-optical comb in one modulating period, which is far smaller than that by the dark-optical comb. This eventually contributes to incomplete mode-locking phenomenon with a huge continuous-wave component in the SOAFL output.

The optimized soliton compression is to operate the dispersion compensation stage at the result of transform limit pulse. The linearly and nonlinearly pulse-compressed SOAFL pulse shapes after passing through dispersion-compensating fiber (DCF) and single-mode fiber (SMF) are shown in Fig. Fig. 4.3.3.5. The linear dispersion compensation of the mode-locked SOAFL pulse is achieved with a 75m-long DCF, which results in a slightly compressed pulsewidth of 3.9 ps due to the large negative dispersion of the DCF. In addition, the soliton-like pulse compression under the interaction between the group velocity dispersion (GVD) and the self-phase modulation (SPM) effects in the SMF has also been employed, which nonlinearly compresses the input SOAFL pulse with high peak-power. The pulse-compression can be constructed entirely by fiber segments with normal and anomalous GVD operating at soliton regime [12], where the maximum pulse energy is theoretically limited to 100 pJ. At higher energy, wave-breaking occurs and is manifested as multiple-pulsing. To perform, additional EDFA is necessary in our case to enlarge the peak power of SOAFL pulse for high-order soliton generation. The SPM generates a frequency chirp such that the leading edge is red shifted and the trailing edge is blue-shifted from the central frequency.

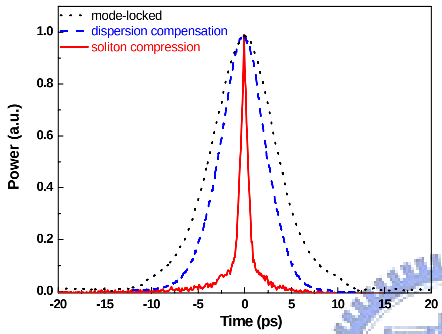


Fig. 4.3.3.5 Comparison of SOAFL pulse shapes after mode-locking (dotted curve), linear dispersion compression (dashed curve) and nonlinear soliton compression (solid curve).

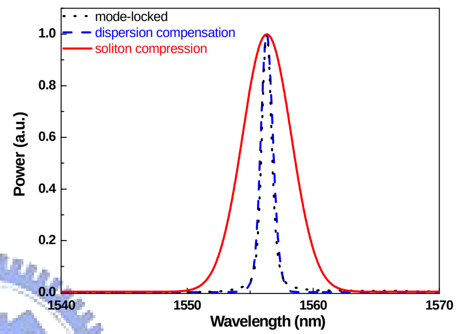


Fig. 4.3.3.6 Lasing spectra of dark-optical comb mode-locked SOAFL pulse before (dotted curve) and after propagating through a 75-m DCF (dashed curve) and a 76.7-m SMF (solid curve).

With the SPM-induced linewidth broadening effect, the finite gain-bandwidth limitation of the SOAFL can be released. Meanwhile, the anomalous GVD compensates such a frequency chirping at a certain propagation distance, resulting in a pulse compression over the central part of the SOAFL pulse. The pulsewidth of the mode-locked SOAFL can be nonlinearly compressed to 560 fs after propagating through a 76.7m-long SMF (D~20 ps/nm·km). The lasing spectra of the mode-locked SOAFL after propagating through the DCF and SMF are plotted in Fig. 4.3.3.6. The spectral linewidth and time-bandwidth product of the original mode-locked SOAFL pulse are 0.9 nm ($\Delta\nu$ = 112.5 GHz) and 0.61, respectively. After propagating the amplified pulse through a 75m-long DCF, the pulsewidth, linewidth and time-bandwidth product become 3.9 ps, 0.9 nm ($\Delta\nu$ = 112.5 GHz) and 0.44, respectively. The nonlinear soliton compression further increases the linewidth of the SOAFL pulse to 4.5 nm ($\Delta\nu$ = 562.5 GHz), corresponding to a transform limited time-bandwidth product of 0.31.

Originally, the mode-locked SOAFL pulses exhibit two orthogonally polarized components since the SOAFL ring cavity is not polarization-mode maintained. Due to the intensity-dependent nonlinear birefringence, the intense central peak and the weak pedestal with orthogonal polarization modes may experience different phase shifts during propagating in the SMF, which inevitably causes a pulse broadening (τ_{FWHM} = 762 fs) and separating phenomenon, as shown in Fig. 4.3.3.7. Such a pulse broadening can be overcome by adding an linear polarizer after the fiber pulse compressor, which has previously been employed by Ahmed *et al.* to demonstrate a 185-fs pedestal-free soliton compressed pulse from gain-switch laser diode system [16]. By rotating the polarization controller, the intense central peak can be fully compensated and changed to a linear polarization state while leaving the pedestal component in a different polarization state. Finally, the tiny pedestal is completely eliminated by detuning the input power at the DCF compensating stage. This results in a shortest pulsewidth of 560 fs.

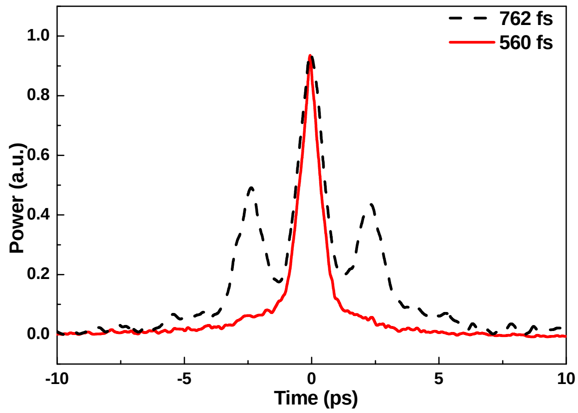


Fig. 4.3.3.7 The suppression of polarization-mode dispersion induced side-lobe in the auto-correlated trace of the backward optical-comb injection-mode-locked SOAFL pulse shapes. Dashed curve: partially controlled polarization mode by adjusting the polarization controller. Solid curve: pedestal-free pulse shape via the fine adjustment of input power at DCF stage.

A nearly transform-limited 4.3-ps pulse-train at 20 GHz over a 16-nm tuning range was also reported under the injection of the DCF compressed 15-ps pulses from a 10-GHz gain-switched DFBLD at 1548.5 nm [8]. Guy *et al.* have also reported a novel 10-GHz actively mode-locked laser operating at 1.3 μm, in which a discrete semiconductor laser amplifier serves only as a gain medium with an electro-absorption amplitude modulator based mode-locker. Such a SOAFL has also generated a nearly transform-limited pulsewidth as short as 1.9 ps [4]. On the other hand, Kim *et al*. have ever observed the compressed pulsewidth of 6.8 ps after passing through a 2-km SMF, which exhibits the linewidth and time-bandwidth product of 0.5 nm and 0.44, respectively [5]. In comparison, our new scheme show a great potential in generating shorter pulses at higher repetition rates after linear chirp compensating and nonlinear soliton compressing process, which already exhibits the shortest and transform-limited subpicosecond pulsewidth to date.

4.4 Conclusions

In conclusion, the dark-optical comb injection-mode-locked SOAFL pulse can further be compressed to 560 fs via the linear dispersion compensation and non-linear compression techniques. A backward dark-optical comb injection induced optically harmonic mode-locking of a semiconductor optical amplifier (SOA) based fiber laser (referred as SOAFL) is demonstrated for the first time. The injected dark-optical comb with 25-ps pulsewidth can be generated using a Mach-Zehnder intensity modulator (MZM) at biased point of 0V. Theoretical simulation indicates that the backward injection of optically dark pulse-train results in a wide gain-depletion width (as well as a narrow gain window of ≤25 ps) within one modulation period, providing a cross-gain-modulation induced mode-locking of the SOAFL with a shortest pulsewidth of 5.4 ps at repetition frequency for 10 GHz. The difficulty in mode-locking the SOAFL by an optical short pulse (bright-optical comb) injection is also demonstrated and explained, which is attributed to the insufficient gain-depletion time (as well as modulation depth). After propagating through a 75m-long DCF and a 76.7m-long SMF, the pulsewidth of the mode-locked SOAFL can be linearly dispersion-compensated to 4 ps and nonlinearly soliton-compressed to 560 fs, respectively. The lasing linewidth and time-bandwidth product of such a dark-optical comb mode-locked SOAFL after compression are 4.5 nm and 0.31, respectively.

4.5 Reference

[4-1] E. Yoshida, Y. Kimura, and M. Nakawa, “20 GHz, 1.8 ps pulse generation from a regeneratively modelocked erbium-doped fibre laser and its femtosecond pulse compression,” Electron. Lett., vol. 31, pp. 377-378, 1995.

[4-2] M. Nakazawa, and E. Yoshida, “A 40-GHz 850-fs regeneratively FM mode-locked polarization-maintaining erbium fiber ring laser,” IEEE Photon. Technol. Lett., vol. 12, pp. 1613-1615, 2000.

[4-3] Lingze Duan, J. K. Richardson, and Julius Goldhar, “A Stable Smoothly Wavelength-Tunable Picosecond Pulse Generator,” *IEEE Photon. Technol. Lett.*, vol. 14, pp. 840- 842, 2002

[4-4] M. J. Guy, J. R. Taylor and K. Wakita, “10 GHz 1.9 ps actively modelocked fibre integrated laser at 1.3 μm,” *Electron. Lett.* vol. 33, 1630-1632, 1997.

[4-5] D. H. Kim, S. H. Kim, Y. M. Jhon, S. Y. Ko, J. C. Jo, and S. S. Choi, “Relaxation-Free Harmonically Mode-Locked Semiconductor-Fiber Ring Laser,” *IEEE Photon. Technol. Lett.* vol. 11, 521-523 (1999).

[4-6] L. Schares, R. Paschotta, L. Occhi, And Guekos, “40-GHz Mode-Locked Fiber-Ring Laser Using a Mach-Zehnder Interferometer With Integrated SOAs,” *J. of Lightwave Technol.* vol. 22, pp.859-873, 2004.

[4-7] D. M. Patrick, “Modelocked ring laser using nonlinearity in a semiconductor laser amplifier,” *Electron. Lett.* vol. 30, 43-44 (1994).

[4-8] T. Papakyriakopoulos, K. Vlachos, A. Hatziefremidis, and H. Avramopoulos, “20-GHz broadly tunable and stable mode-locked semiconductor amplifier fiber ring laser” *Opt. Lett.*, vol. 24, pp. 1209-1211, 1999.

[4-9] M. W. K. Mak, H. K. Tsang, and H. F. Liu, “Wavelength-tunable 40 GHz pulse-train generation using 10 GHz gain-switched Fabry-Perot laser and semiconductor optical amplifier,” *Electron. Lett.* vol. 36, pp 1580-1581, 2000.

[4-10] Kyriakos Vlahos, Chris Bintjas, Nikos Pleros, and Hercules Avramopoulos, "Ultrafast semiconductor-based fiber laser sources," *IEEE Journal Of Selected Topics In Quantum Electronics*, vol. 10, pp. 147-153, 2004.

[4-11] K. S. Abedin, and F. Kubota Yoshida, "Wavelength tunable high-repetition-rate picosecond and femtosecond pulse sources based on highly nonlinear photonic crystal fiber," *IEEE J. Quantum Electron.*, vol. 10, pp. 1203-1210, 2004.

[4-12] K. Tamura, J. Jacobson, H. A. Haus, E. P. Ippen, and J. G. Fujimoto, "77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser," *Opt. Lett.*, vol. 18, pp. 1080-1082, 1993.

[4-13] K. A. Ahmed, H. H. Y Cheng, and H. F. Liu, "Generation of 185fs pedestal-free pulses using a 1.55μm distributed feedback semiconductor laser," *Electron. Lett.* vol. 31, pp 195-196, 1995.

[4-14] L. P. Barry, B. C. Thomsen, J. M. Dudley, and J. D. Harvey, "Optimised design of fibre-based pulse compressor for gain-switched DFB laser pulses at 1.5μm," *Electron. Lett.*, vol. 35, pp. 1166-1168, 1999.

[4-15] H. F. Liu, Y. Ogawa, S. Oshiba, and T. Nonaka, "Relaxation-free harmonically mode-locked semiconductor-fiber ring laser," *IEEE Journal Of Quantun Electronics.*,vol. 11**,** pp. 1655-1660, 1991.

[4-16] K. A. Ahmed, K. C. Chan, and H. F. Liu, "Femtosecond pulse generation from semiconductor lasers using the soliton-effect compression techique," *IEEE J. Quantum Electron.*, vol. 1**,** 592-600, 1995.

[4-16]L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Extreme picosecond pulse narrowing by means of soliton effect in single-mode optical fibers," *Opt. Lett.*, vol. 8, pp. 289-291, 1983.