# Femtosecond wavelength tunable semiconductor optical amplifier fiber laser mode-locked by backward dark-optical-comb injection at 10 GHz

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**Abstract:** Femtosecond nonlinear pulse compression of a wavelength-tunable, backward dark-optical-comb injection harmonic-mode-locked semiconductor optical amplifier based fiber laser (SOAFL) is demonstrated for the first time. Shortest mode-locked SOAFL pulsewidth of 15 ps at 1 GHz is generated, which can further be compressed to 180 fs after linear chirp compensation, nonlinear soliton compression, and birefringent filtering. A maximum pulsewidth compression ratio for the compressed eighth-order SOAFL soliton of up to 80 is reported. The pedestal-free eighth-order soliton can be obtained by injecting the amplified pulse with peak power of 51 W into a 107.5m-long single-mode fiber (SMF), providing a linewidth and time-bandwidth product of 13.8 nm and 0.31, respectively. The tolerance in SMF length is relatively large (100-300 m) for obtaining <200fs SOAFL pulsewidth at wavelength tuning range of 1530-1560 nm. By extending the repetition frequency of dark-optical-comb up to 10 GHz, the mode-locked SOAFL pulsewidth can be slightly shortened from 5.4 ps to 3.9 ps after dispersion compensating, and further to 560 fs after second-order soliton compression. The lasing linewidth, time-bandwidth product and pulsewidth suppressing ratio of the SOAFL soliton become 4.5 nm, 0.33, and 10, respectively.



**OCIS codes:** (250.5980) Semiconductor optical amplifier; (140.4050) Mode-locked lasers; (320.5520) Pulse compression

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## 1. Introduction

Mode-Locked semiconductor optical amplifier (SOA) based fiber laser (referred as SOAFL) is typically implemented by directly gain modulating the SOA via a periodically controlled driving current. With such technique, a mode-locked SOAFL pulsewidth as short as 1.9-ps at repetition rate as high as 10 GHz was previously demonstrated [1]. During the past decade, an all-optical cross-gain modulation (XGM) scheme has also been performed for mode locking the SOA by periodically depleting its gain via forward optical injection. Later on, the backward optical injection induced periodical-gain-depletion in SOA was experimentally demonstrated to achieve XGM mode locking of the SOAFL [2-11]. Notably, Patrick [2] used an all-optical modulated SOA as a mode-locker to construct an actively rational-harmonic mode-locked EDFL with 8.4 ps pulsewidth at 20 GHz. Similar result was done by optically gain depleting an SOA with a gain-switched and pulse-compressed distributed-feedback laser diode (DFBLD) [3], while the SOA was acting as both a gain medium and an optically controlled mode-locker for the SOAFL. After a fast gain-depletion of the SOA following by a strong optical pulse injection, the mode locking can be initiated as the gain of SOA slowly recovers back to overcome the cavity loss. Such a technique is capable of generating single- and multi-wavelength mode-locked pulses at repetition frequency of 5-40 GHz [3-4] and 30 GHz [5-6], respectively. Recently, an adopted traveling-wave rate-equation model has been established to simulate the build-up dynamics of the mode-locked SOAFL pulses [10]. The effects of the XGM waveform on the pulse shape of the backward optical-injection mode-locked SOAFL were also investigated [11]. We have also reported a shortest mode-locked SOAFL pulsewidth of 12 ps at repetition frequency of 5 GHz, which is obtained under the backward injection of an externally digital-TTL-pattern modulated DFBLD with an optimized duty cycle [11]. Taking the concept, a backward dark-optical-comb injection technique was primarily applied to mode-lock the SOAFL and to generate 15ps pulsewidth at repetition frequency of 1 GHz [12].

On the other hand, a nearly transform-limited pulse-train with 4.3-ps duration at 10-20 GHz over a tuning range 16-nm can be obtained by compensating the dispersion of XGM mode-locked SOAFL pulse [3]. Similar result [13] on the compression of mode-locked SOAFL pulse with a 2-km standard single-mode fiber (SMF) was also demonstrated to generate a transform-limited pulsewidth and linewidth of 6.8 ps and 0.5 nm, respectively. Nowadays, the XGM mode-locked SOAFL with a highest repetition rate up to 50 GHz [9], a shortest pulsewidth of 4.3 ps [3], and a wide wavelength tuning range of ~20 nm [9] have been reported. Nonetheless, it is found that most XGM mode-locked SOAFL systems generate pulses in picosecond regime [3, 11, 13-14], whereas the XGM mode-locked SOAFL system with femtosecond pulsewidth was not investigated. In this paper, we study the femtosecond soliton compression dynamics, the wavelength tuning and high-repetition frequency results of

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a backward dark-optical-comb injection induction XGM mode-locked SOAFL. The dark optical comb is employed as a novel modulating waveform with an adjustable duty cycle, which can be generated by seeding a DFBLD output into an electrical-comb biased Mach-Zehnder modulator (MZM). The SOA based XGM mode-locker is periodically gain-depleted by backward injecting the dark-optical-comb, such a scheme offers a much wider modulation bandwidth as compared to the directly electrical modulation approach. Picosecond dispersion compensation and femtosecond high-order soliton compression of such a novel backward dark-optical-comb injection mode-locked SOAFL pulse at repetition frequency up to 10 GHz is demonstrated for the first time. The effects of input pulse power and the fiber length on the pulsewidth and the time-bandwidth product of high-order femtosecond soliton are discussed. The wavelength tunability of such an optical-injection mode-locked SOAFL system is also characterized.

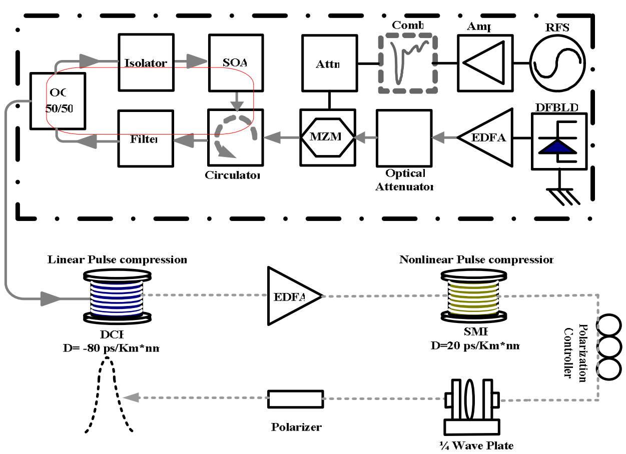


Fig. 1. Schematic diagram of backward-optical-injection mode-locked SOAFL based femtosecond soliton generator. ATTN: attenuator; Amp: power amplifier; COMB: comb generator; DFBLD: distributed feedback laser diode. EDFA: erbium-doped fiber amplifier; ISO: isolator; MZM: Mach-Zehnder modulator; OC: optical coupler; RFS: RF synthesizer.

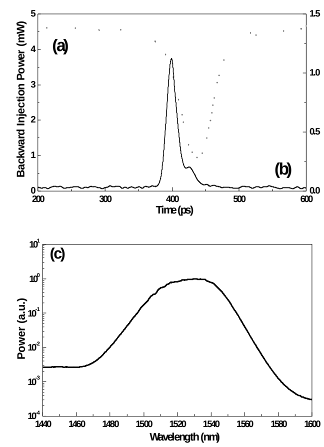


Fig. 2. Upper: pulse shapes of the (a) injected dark-optical-comb and (b) mode-locked SOAFL; Lower: (c) the amplified spontaneous emission spectrum of SOA operated at 15°C.

## 2. Experimental

Figure 1 illustrates the backward-optical-injection mode-locked SOAFL system with a ring cavity length of 14 m, which consists of one traveling-wave typed SOA at 1530 nm, an optical circulator, a faraday isolator, a polarizer, an 50% output coupler (OC), an optical tunable band-pass filter (OBPF), a quarter-wave plate, and a polarization controller. The SOA is polarization insensitive with its maximum polarization dependent gain deviation of <1.5 dB. The SOA with central wavelength and spectral linewidth of 1530 nm and 35 nm, respectively, was DC biased at 345 mA (well above threshold current of 50 mA). To backward optical-inject the SOA for harmonic mode-locking, a butterfly-packaged DFBLD operated at 70 mA, 1535 nm, and 25°C was amplified by an EDFA with 20dB gain and externally modulated by a MZM. The electrical comb generator used to drive the MZM is triggered by an amplified microwave signal with power of 29 dBm. By operating the DC-bias level of the MZM at ~0.2 $V_\pi$, a dark-optical-comb with average power and pulsewidth of 4.46 mW and ≤60 ps, respectively, can be obtained at the MZM output, as illustrated in Fig. 2. The dark optical-comb is backward injected into the SOAFL via an optical circulator, which then induces a gain-depletion modulation depth of nearly 100% under fine adjustment of the SOA driving current. The OBPF exhibits a 3dB bandwidth of 1.2 nm, which facilitates the mode locking and avoids the lasing of the injected dark optical-comb in the SOAFL. The harmonic mode locking of SOAFL is achieved when the repetition frequency of the injected dark optical-comb coincides with one harmonics of the longitudinal mode in the SOAFL.

For nonlinear soliton generation, the peak power ($P_N$) of the input pulse required to obtain the $N^{th}$-order soliton was theoretically derived as [15]

$$P_N = 3.11N^2 \frac{D\lambda^2}{2\pi c \gamma \tau^2}, \quad (1)$$

where $\lambda$ is the signal wavelength, c is the light velocity, and $\gamma$ = 1.3 $W^{-1}$ $km^{-1}$ is the nonlinearity coefficient for a fiber with a core diameter of 9.3 μm. The compression ratio increases with an increasing N [16]. The optical soliton is the result of interaction between the group velocity dispersion (GVD) and the self-phase modulation (SPM) effects in a fiber with anomalous dispersion. The frequency chirp induced by SPM (with a red-shifted leading edge and blue-shifted trailing edge) is simultaneously compensated by anomalous GVD after propagating through a certain distance. These two effects eventually balances each other to generate fundamental soliton traveling in a lossless fiber without any temporal and spectral changes, or to obtain higher order soliton with its original shape periodically recurring at multiples of the soliton period $Z_0$ given by [14]

$$Z_0 = 0.332\frac{c}{D}\left(\frac{\tau\pi}{\lambda}\right)^2 = 0.332\frac{\pi\tau^2}{2|\beta_2|}, \quad (2)$$

Subsequently, the residual chirp of SOAFL pulses were linearly compensated using a DCF (with dispersion parameter of *D* = -80 ps/km/nm). The SOAFL pulses were pre-amplified with the average input power remaining at <45 mW to avoid the self-phase modulation occurred at DCF stage. To perform soliton effect compression, the dispersion compensated pulse-train was amplified by a booster EDFA with output power of 440 mW, and was then coupled into the SMF spool (*D* = 20 ps/km/nm) with different lengths. The pulse shapes of the compressed soliton at different orders were further reshaping with a birefringent filter [15]. A polarization controller was employed to control the input polarization state of the soliton pulse. A quarter-wave plate was used to compensate the phase shift and to reconstruct linear and orthogonal polarization states for the principle and side-lobe of soliton pulse. Afterwards, a linear polarizer was used to filter out the side-lobe of soliton pulses with orthogonal polarization state. By fine-tuning such a birefringent filter located behind the SMF spool, the pulse shape after soliton effect compression can be completely pedestal-free.

### 3. Results and discussion

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. 2(a), the optimized mode-locking result of the SOAFL is illustrated in Fig. 2(b). 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 mW. 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. Theoretically, a relatively broadened and residual gain window of the SOA within one modulation period is less contributed to the initiation of harmonic mode locking in the SOAFL. Note that a sufficiently

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narrow gain-window is particularly important to the initiation of mode-locking process. In comparison, the harmonic mode locking of SOAFL is relatively easy to be established via the backward injection of an optically sinusoidal waveform instead of a bright-optical-comb pulse shape. In frequency-domain analysis, a short-pulse modulation waveform will transfer the power to harmonics and reduce the power in the fundamental frequency. This eventually leads to a weak mode-locked pulse accompanied with a larger gain-depleted hole. Consequently, the continuous-wave lasing of SOAFL is more pronounced than its harmonic mode-locking. A periodically spatial hole is generated due to the gain reduction of SOAFL under the backward injection of bright-optical-comb pulse. The simulating result reveals that the continuous-wave lasing part (i.e. the pedestal happened after the principle pulse) can be narrower in time-domain when the pulsewidth of the bright-optical-comb becomes wider, or which can be suppressed as the peak amplitude of the gain-switched FPLD becomes larger. That is, the lengthened high-level duration (i.e. a larger duty cycle) of the backward optical injection waveform can temporally shrink the gain window, which is mandatory to obtain the short mode-locking pulsewidth of the SOAFL. The shorter pulsewidth of the mode-locked SOAFL as compared to that of the injected dark-optical-comb is due to the gain recovery time needed for the SOA to overcome the cavity loss. Even though the gain recovery process is relatively fast in the SOA, it still takes time for the SOA to build up its gain after a strong and long-term depletion. This results in a gain window that is narrower than the pulsewidth of dark-optical-comb, corresponding to a shorter mode-locked SOAFL pulsewidth eventually.

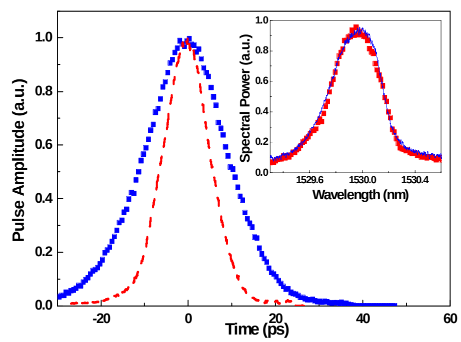


Fig. 3. Auto-correlated traces and lasing spectra of SOAFL pulse before and after chirp compensation.

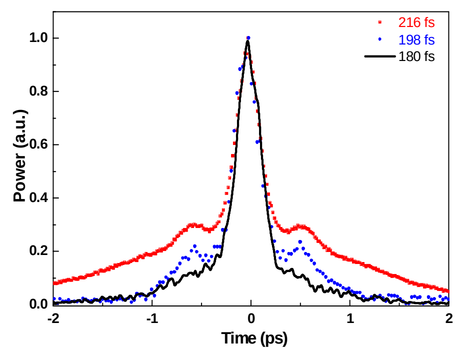


Fig. 4. Original (dotted), partially birefringent filtered (dashed) and completely filtered (solid) soliton pulses

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 ($\Delta\nu$ = 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 [13]. 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 [17]. 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. (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 [18]. 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. 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. To suppress these pedestals, an intensity discrimination scheme that relies upon the intensity dependent polarization separation is utilized in our work [15, 16]. 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.

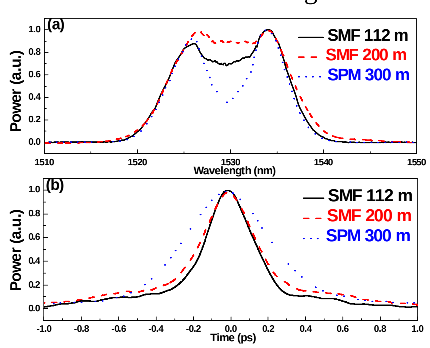


Fig. 5. Comparison on the pulsewidth and linewidth of the eighth-order soliton pulses compressed by SMF with different lengths.

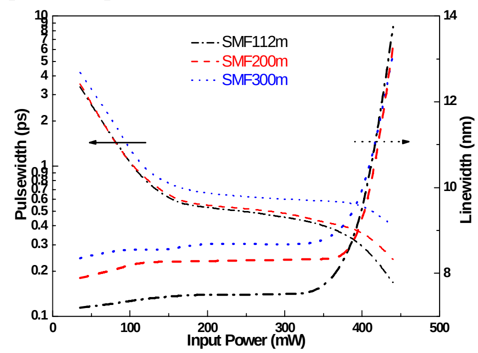


Fig. 6. Pulsewidth and linewidth of nonlinear compressed SOAFL pulse at different input powers and SMF lengths.

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. 5 and 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. 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. 5(a). At input power of 440 mW, the auto-correlation traces of the compressed pulses output from

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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. 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. 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. 6.

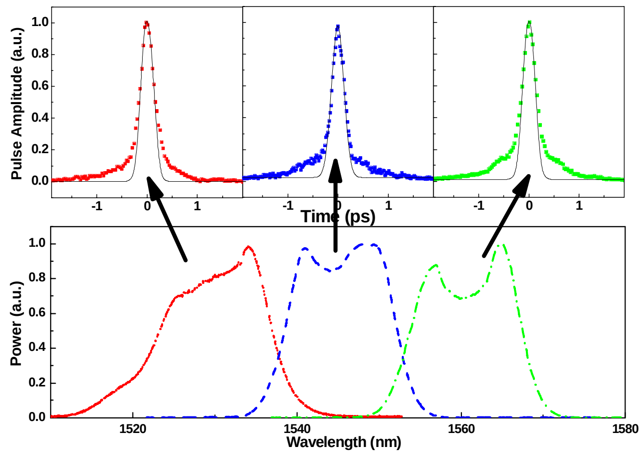


Fig. 7. The nonlinearly compressed pulse shapes and associated spectra at different SOAFL wavelengths.

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.

Finally, the mode-locking and femtosecond compression for the backward dark-optical-comb injected SOAFL at repetition frequency of 10 GHz is primarily demonstrated. The dark-optical-comb with 25-ps pulsewidth at 10 GHz is generated from a MZM driven by a commercial electrical comb with peak voltage of 11.2 volts at a DC offset of 0 volt. The optimized mode-locking scheme is to operate the SOA at a high-gain condition and then gain-deplete the SOA via a high-power dark-optical comb shown in Fig. 8(a). Such a backward

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dark-optical-comb injection results in a narrow gain window of 25 ps within one modulating period, providing a mode locking of the SOAFL with a shortest pulsewidth of 5.4 ps at 10 GHz. In comparison, there was only a report for generating a nearly transform-limited 4.3-ps pulse-train over a 16-nm tuning range from a similar SOAFL system under the injection of the 15-ps gain-switched and DCF compressed DFBLD pulses repeated at 10 GHz [3]. The peak power of the mode-locked SOAFL pulse-train shown in Fig. 8(b) is 2.45 mW. On the contrary, the backward injection of a bright-optical-comb (see Fig. 8(c)) with short pulsewidth fails to induce sufficient modulation depth in the SOA, giving rise to a mode locking with a secondary pulse shown in Fig. 8(d). The linearly compensated and nonlinearly compressed SOAFL pulse shapes after passing through DCF and SMF are shown in Fig. 9. The spectral linewidth and time-bandwidth product of the original mode-locked SOAFL pulse are 0.9 nm and 0.61, respectively. The mode-locked SOAFL pulsewidth can be slightly shortened to 3.9 ps with a 75m-long DCF. By amplifying the average power DCF compensated SOAFL pulse up to 1.7 W, the second-order soliton can be generated with its pulsewidth, linewidth and time-bandwidth product of 560 fs, 4.5 nm and 0.33, respectively, after nonlinearly soliton compressing in a 76.7m-long SMF. The inevitable broadening of the compressed pulsewidth at 10 GHz as compared to that at 1 GHz is due to the low-order soliton compression occurring at such high repetition frequency. This is mainly attributed to the lower peak power (about 11 W) obtained from the booster EDFA (operated at saturating condition with constant average power of 0.44 W) at higher repetition frequency and the shorter pulsewidth obtained at the DCF compensating stage, which concurrently result in the decreasing soliton order.

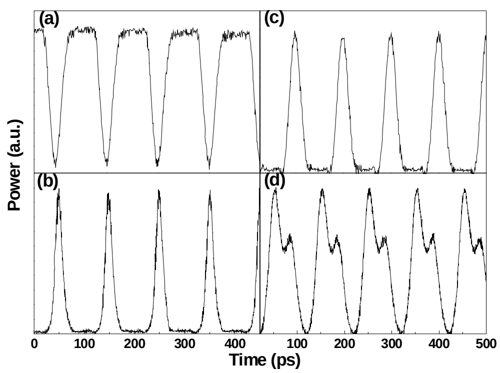


Fig. 8. Backward injected (a) dark- and (b) bright-optical- combs, and their resulting mode-locked SOAFL pulse-trains shown in (c) and (d), respectively.

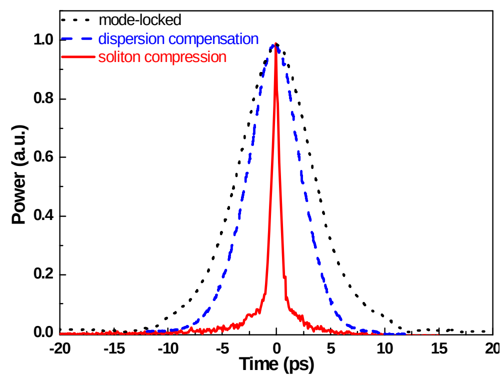


Fig. 9. Mode-locked (dotted), dispersion compensated (dashed), and soliton compressed (solid) SOAFL pulse shapes obtained at repetition frequency of 10 GHz

## 4. Conclusion

We have primarily investigated the femtosecond soliton compression and wavelength tuning of a backward dark-optical-comb injection mode-locked SOAFL at repetition frequency of 1-10 GHz. The shortest pulsewidth of 180 fs at repetition frequency of 1 GHz after linear dispersion compensation, nonlinear soliton compression and birefringent filtering is demonstrated. After propagating through a 420 m-long DCF for dispersion compensation, the mode-locked SOAFL shrinks its pulsewidth and TBP to 8.6 ps and 0.48, respectively, without changing its spectral linewidth. The DCF compensated SOAFL pulse is further amplified to a peak power of 51 W for eighth-order femtosecond soliton generation. Theoretical calculation on the optimized SMF length of 107.5 m for nonlinear soliton compression is provided. The nonlinear soliton compression further increases the linewidth of the SOAFL pulse to 13.8 nm ($\Delta\nu$=1.7 THz), while the TBP is reduced to a transform-limit of 0.31. By using a birefringent filter, a maximum pulsewidth compression ratio of 80 for the 180 fs pedestal-free SOAFL soliton pulse is reported to date. The effect of SMF length on the pulsewidth, the linewidth

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and the TBP of the SOAFL soliton with a maximum wavelength tuning range of up to 30 nm is experimentally characterized. By extending the repetition frequency of dark-optical-comb up to 10 GHz, the mode-locked SOAFL pulsewidth can be slightly shortened from 5.4 ps to 3.9 ps after dispersion compensating, and further to 560 fs after second-order soliton compression. The lasing linewidth, the time-bandwidth product and the pulsewidth suppression ratio of the SOAFL soliton become 4.5 nm, 0.33, and 10, respectively.

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