50 fs soliton compression of optical clock pulse recovered from NRZ data injected SOAFL

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Abstract: Mode-locking of semiconductor optical amplifier fiber laser (SOAFL) with 50 fs pulses by extracting the clock of an optical non-return-to-zero (NRZ) data injection is demonstrated. The efficiency of mode-locking in the SOAFL is improved by increasing the seeding power of the large-duty-cycle NRZ data from 3 to 8 dBm into the SOA driven at biased current of 350 mA. After linear dispersion compensation, the mode-locked SOAFL pulsewidth can be further shortened from 20 to 3 ps by increasing the DCF length up to 110 m. By using a booster the EDFA to enlarge the average power of mode-locked SOAFL pulse to 1.3 W, the shortest soliton pulse is occurred after propagating through a 12-m-long SMF. The amplified SOAFL pulse can be compressed to 50 fs after nonlinear compression with its spectral linewidth broadening to 64 nm. Nearly transform-limited time-bandwidth product of 0.436 and the maximum pulse compressing ratio of 400 are reported to date.

OCIS codes: (250.5980) Semiconductor lasers; (140.3520) Lasers, injection-locked; (140.3510) Laser, fiber; (140.4050) mode-locked lasers.

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1. Introduction

Several-tens femtosecond (fs) optical soliton generated by compressing the passively or actively mode-locking fiber laser pulses has been comprehensively investigated during the past two decades. Since 1993, the soliton compression in a passively mode-locking Erbium-doped fiber laser (EDFL) with a nonlinear amplifying loop mirror was demonstrated to deliver a pulsewidth as short as 50 fs [1]. The significant progress on shortening the pulse of such passively mode-locked fiber laser soliton was not reported until 2004. With the emergence of a highly nonlinear dispersion shifted fiber (DSF), the highly chirped fiber laser pulse can further be compressed to 34 fs during supercontinuum generation [2]. After passing through the highly nonlinear DSF, the widely tunable 24-fs EDFL pulses with spectral linewidth exceeding 100 THz (from 1130 to 1950 nm) have been reported [3]. In 2005, the high-power and octave-spanning supercontinuum EDFL pulses with a peak power of 43 kW and a compressed pulsewidth of 42 fs were achieved [4]. In terms of the dual-stage single-mode fiber (SMF) and large-effective-area- fiber (LEAF), the soliton compression of a self-started additive mode-locked-EDFL pulse has also emerged for 48-fs soliton pulse generation, providing a maximum pulse-width compression ratio of 7 and an optimized pulse-energy confining ratio up to 85% [5]. Additionally, the soliton self-frequency shift effect of the additive-pulse mode-locked EDFL was also observed when obtaining 29-fs pulsewidth in a large-mode-area EDFA [6]. Similar design using linear compression in photonic band-gap fiber and soliton compression in highly nonlinear fiber was subsequently proposed for 20-fs pulse generation [7]. Simple designs for intra-cavity soliton compression in a passively nonlinear-polarization-rotation mode-locked EDFL with 2-nJ and 47-fs pulsewidth, and the 13-fs pulses from a two-branch wavelength tunable EDFL with attosecond relative timing jitter have recently been developed [8,9]. Alternatively, the four-stage soliton compression of the gain-switching laser diode (GSLD) pulse was also reported with shortest pulsewidth approaching 20 fs in 1999 [10]. Later on, a simplified single-stage high-order soliton compressor two kinds of step-like dispersion profiled fibers of only 15-m long was employed to shorten the GSLD pulsewidth from 5 ps to 20 fs [11]. Relatively few works were emerged before year 2000 for compressing < 100-fs actively mode-locked fiber laser pulses. In 2000, a 850-fs regeneratively FM mode-locked polarization-maintaining EDFL at 40 GHz has been proposed [12]. Subsequently, a 12-m long photonic crystal fiber based Raman soliton has emerged to compress the actively mode-lock the EDFL pulsewidth to 176-fs at 10-GHz repetition rate, which further provides tunable wavelength range up to 90 nm by means of soliton self-frequency shift effect [13]. More recently, the supermode-noise-free eighth-order soliton has been successfully generated from a backward dark-optical-comb-injection mode-locked semiconductor optical amplifier fiber laser (SOAFL) [14]. With dispersion-compensated fiber based chirp compensator and single-mode fiber based soliton compressor,

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the actively mode-locking SOAFL pulse can be greatly shortened from 15 ps to 186 fs. Such a scheme offers an ultrahigh pulse-compression ratio of 43 and side-mode suppressing ratio of 87 dB for the eighth-order SOAFL soliton. Nonetheless, the SOAFL was only soliton compressed to 410 fs at repetition rate of 10 GHz after amplification [15].

Owing to the need of all-optical format conversion and carrier generation between non-return-to-zero (NRZ) and return-to-zero (RZ) data streams for interfacial linking between dense-wavelength-division and the time-division multiplexing (DWDM and TDM) hybrid networks, we demonstrate for the first time the soliton compression of an SOAFL mode-locked under the external injection of a single-channel optical non-return-to-zero (NRZ) data-stream at 1555.75 nm dropped from a simulated dense-wavelength-division-multiplexing (DWDM) fiber-optic network at data rate of 1 Gbit/s. Our proposed system intends to recover the clock frequency and to generate the RZ pulsed carrier from the dropped optical NRZ data stream simultaneously. After amplifying by a 1.3-W booster EDFA to achieve sufficiently high soliton order for largest pulse compressing ratio, the relationship between SOA biased current and TTL injection power is thoroughly investigated to optimize the mode-locking and soliton compressing performances.

2. Experiment setup

In the SOAFL ring cavity shown in Fig. 1, a commercially fiber-pigtailed SOA (Qphotonics, QSOA-1550) was employed as the gain medium. The clockwise isolator is used to control the direction of light, and the polarization controller is used to control the polarization of light.

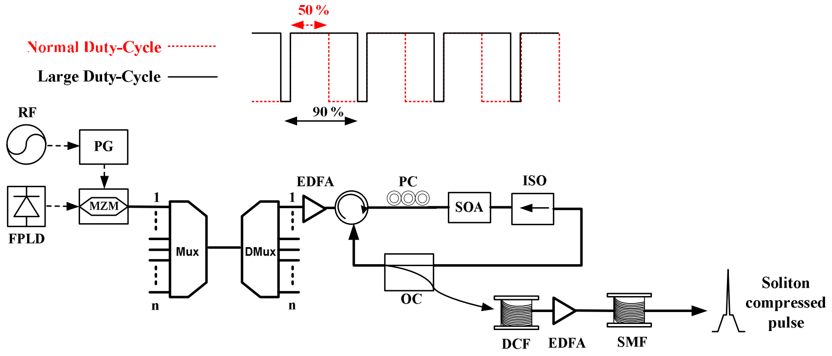

Fig. 1. The experimental setup of the SOAFL under optical NRZ injection. FPLD: Fabry-Perot laser diode, Mux/DMux: multiplexer/demultiplexer, DCF: dispersion compensation fiber, EDFA: Erbium doped fiber amplifier, ISO: Isolator, MZM: Mach-Zehnder intensity modulator, OC: optical coupler, PG: pattern generator, RF: RF synthesizer, SMF: single-mode fiber.

To optimize injection mode-locking of the SOA, a TTL signal with its duty-cycle enlarged from 50% to 90% was generated from a 1 GHz pattern generator (PG, HP70843B) driven by a 1 GHz frequency synthesizer (Agilent). The TTL signal is amplified via an microwave driver amplifier (JDSU) before driving the Mach-Zehnder intensity modulator (MZM) with a half-wave voltage of $V_\pi = 4.5V$. Large-duty-cycle injection reduces the gain of SOA and provides the narrow gain window in SOA, which initiates the pulsed mode-locking of the SOAFL after detuning the TTL repetition frequency to match the harmonics of the SOAFL cavity longitudinal mode. Afterwards, a similar architecture was then employed for mode-locking the SOAFL under the injection of an optical NRZ data-stream generated from the PG at 1 Gbit/s. The optical injection of 7 dBm at 1555.7 nm was employed to achieve the best on-off extinction ratio, which is obtained by seeding the tunable laser output through the amplified NRZ-driven MZM at DC bias of $3V_\pi/4$.

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3. Results and discussions

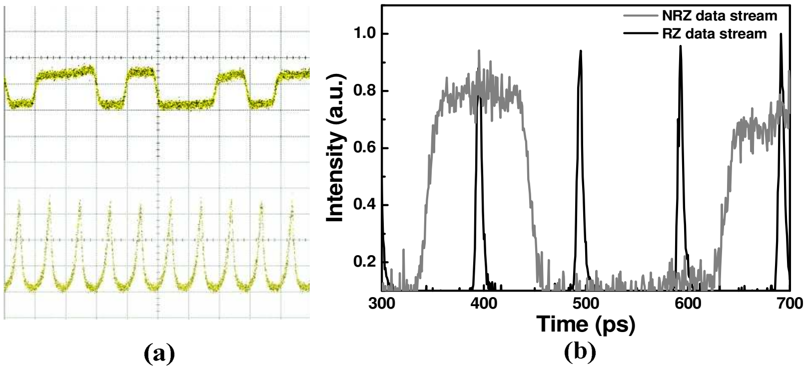

Fig. 2. The shapes of (a) the optical NRZ data stream (b) the recoverd pulsed RZ clock from the SOAFL after optical NRZ injection.

The shape of optical NRZ data stream at the MZM output obtained by tuning the dc-bias level of MZM is shown in Fig. 2(a). The optical NRZ data stream is employed as an injecting source to temporally deplete the gain of the SOA, and the frequency of NRZ data stream is fine tuned to match the intra-cavity frequency. The mode-locking SOAFL is initiated when setting the SOA biased-current at 350 mA and detuning the optical NRZ injection power from 3 to 8 dBm. The pulsed RZ clock demonstrated by actively mode-locking the SOAFL is shown in Fig. 2(b).

By enlarging the average power of the optical NRZ form 3 to 8 dBm to inject SOA at biased current of 350 mA, the Fig. 3(a) shows that the mode-locking SOAFL pulsewidth is effectively decreased from 30 to 20 ps. This result is attributing to the empirical mode-locking pulsewidth equation $\tau_p = [(2\ln 2)^{1/2}/\pi][2g_0/(\delta^2 \cdot f_m{}^2 \cdot \Delta\nu^2)]^{1/4}$ [21], where τ_p is the pulsewidth, g_0 is the single-pass integrated gain of SOA, f_m is the modulation frequency, δ is the modulation depth, and $\Delta\nu$ is the spectral linewidth. The modulation depth is deeper by seriously depleting the SOA gain with stronger injection power. Therefore, the mode-locking SOAFL pulsewidth is shortened based on the strong injection of the optical NRZ data stream. In the meantime, we find that the timing jitter is greatly suppressed to 200 fs when the optical NRZ injection power is strong enough to reduce the phase noise generated by the ASE of the SOA, as shown in Fig. 3(b).

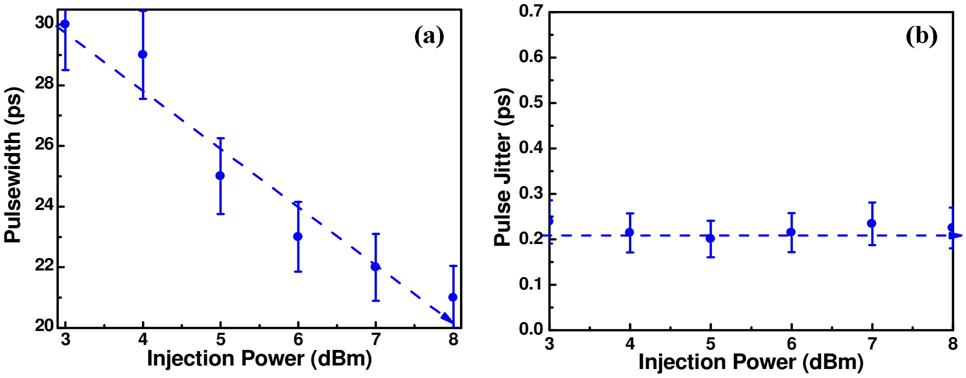

Fig. 3. (a) The pulsewidth of mode-locking SOAFL at different injection powers. (b) The jitter of mode-locking SOAFL at different injection powers.

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By increasing the optical NRZ injection power, we also observe that the mode-locking of SOAFL is gradually completed with the DC level of the output pulse greatly decreased from 85 to 35 μW, whereas the SOAFL pulse peak power maintains at around 3800 μW when the mode-locking is initiated with sufficient optical NRZ injection power, as shown in Fig. 4(a). The Fig. 4(b) shows a maximum pulse peak power/DC level contrast ratio up to 20 dB can be achieved at highest injection condition. As a result, the strong optical NRZ injection effectively reduces the ASE sustained in the SOA, such that the mode-locking mechanism becomes dominant to win the gain competition in the SOAFL under strong injection case. We can ascertain that the mode-locking quality of SOAFL by calculating the ratio of pulse peak power to DC level.

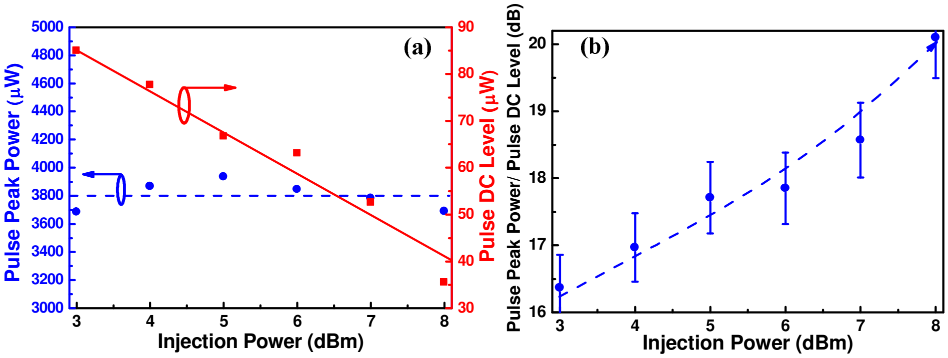

Fig. 4. (a) The pulse peak power and DC level of mode-locking SOAFL at different injection powers. (b) The ratio of pulse peak power to DC level with increasing the injection powers.

After obtaining the mode-locked SOAFL pulse under external NRZ injection power of 8 dBm and SOA biased current of 350 mA, the spectrum of mode-locked SOAFL pulse red-shifts toward 1558 nm, whereas the ASE component of the SOA gradually diminishes with increasing NRZ injection. The mode-locked SOAFL spectral linewidth is about 4 nm. Figure 5(a) shows the comparison between the originally mode-locked, linearly dispersion-compensated and soliton compressed SOAFL pulses. When appropriate dispersion compensation is achieved to obtain a chirp-free pulse before soliton compression, the mode-locked SOAFL pulsewidth is shortened from 20 to 3 ps with time-bandwidth product (TBP) of 1.48 by inserting a 110-m long DCF. After calculation, a 12-m long SMF is employed to obtain ninth-order soliton with its pulsewidth shortening from 3 ps to 50 fs and the linewidth broadening from 4 to 64 nm, as shown in Fig. 5(b). The nine-order soliton approaches a TBP of 0.436 (nearly the transform-limited Gaussian pulse with TBP of 0.44).

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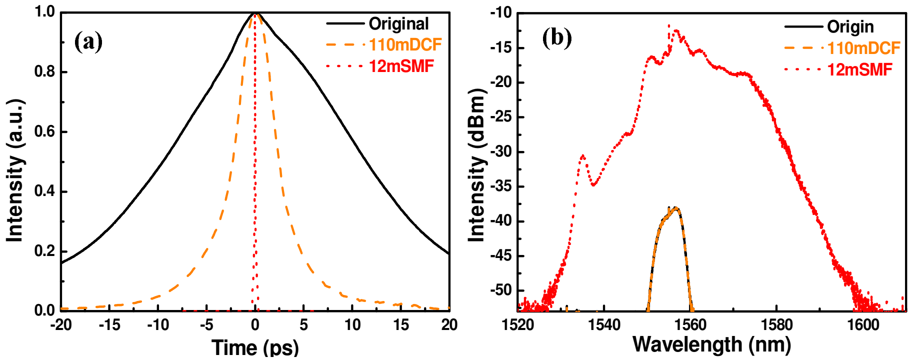

Fig. 5. (a) Mode-locked (black), dispersion compensated (orange), and soliton compressed (red) SOAFL pulses. (b) Mode-locked (black), dispersion compensated (orange), and soliton compressed (red) SOAFL spectra.

After mode-locking, the SOAFL spectrum for mode-locked pulse red-shifts toward 1558 nm, and the ASE component of the SOA gradually diminishes with increasing NRZ injection. Even though, there is still a residual continuous-wave component observed at 1555.75 nm, which is originated from the optical NRZ injection associated with the soliton spectrum. This results in a gain competition between the residual optical NRZ component and mode-locked SOAFL pulse within the booster EDFA, such that the optimized soliton is obtained at a slightly long distance as expected. For specific application in super-continuum generation, a second-stage soliton compressor is needed.

4. Conclusion

Under external NRZ injection power of 8 dBm, we obtain the mode-locked pulse from SOAFL with its pulsewidth shortening from 30 to 20 ps and its timing jitter decreasing to 200 fs at SOA bias current of 350 mA. The mode-locked pulse is optimized in SOAFL with its DC level greatly decreasing from 85 to 35 μW (only 0.96% of the mode-locked pulse peak power) while maintaining the pulse peak power at 3800 μW to maximum the pulse peak power/DC level contrast ratio up to 20 dB. The 110-m long DCF based dispersion compensation further shortens the mode-locked SOAFL pulse from 20 to 3 ps without changing its spectral linewidth of 4 nm. The shortest ninth-order soliton pulsewidth of 50 fs is achieved by using 12-m long SMF to compress the EDFA amplified SOAFL pulse, providing a TBP of 0.436 and a total pulse compressing ratio up to 400.

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