110-pJ and 410-fs Pulse at 10 GHz Generated by Single-Stage External Fiber Compression of Optically Injection-Mode-Locked Semiconductor Optical Amplifier Fiber Laser

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***Abstract*—We demonstrate the high-power amplification and single-stage fiber-based pulse compression of a traveling-wave semiconductor optical amplifier (TWSOA) fiber ring laser (SOAFL), which is optically mode-locked by backward injecting the TWSOA with a dark-optical-comb at repetition frequency of 10 GHz. A negatively chirped SOAFL pulsewidth of 5.4 ps is compensated and shortened to 3.9 ps by a 75-m-long dispersion compensating fiber. With a single-stage pulse compression in a single-mode-fiber spool, the SOAFL pulses with input average power of 1.7 W can further be compressed to a pulsewidth of 410 fs, corresponding to a pulse compressing ratio of nearly ten. The maximum average output power of the amplified SOAFL pulse is up to 1.1 W, corresponding to the peak power and pulse energy of >0.27 kW and 110 pJ, respectively.**

***Index Terms*—Cross-gain modulation (XGM), femtosecond, fiber laser, injection-mode-locking, pulse compression, semiconductor optical amplifier (SOA).**

I. INTRODUCTION

THE actively mode-locked traveling-wave semiconductor optical amplifier (TWSOA)-based fiber-ring lasers (referred hereafter as SOAFLs) have been implemented either by directly gain-modulating the TWSOA via a periodically controlled driving current, or by adding an intracavity integrated electrooptic or electroabsorption modulator for loss-modulation [1]–[4]. Alternatively, the mode-locking of EDFLs or SOAFLs can also be achieved by using optical-injection controlled TWSOA [5]–[7] or laser diode [8]. In particular, the optical-injected TWSOA can serve as both the gain medium and the mode-locker in an SOAFL system [9]–[11], while the externally optical injection is periodically depleting the gain of the TWSOA such that the mode-locking can be obtained via cross-gain modulation (XGM) at other wavelengths [12]. The generation of single-wavelength and multichannel picosecond optical pulses from such mode-locked SOAFLs at repetition frequency of 10–40 GHz were reported recently [13], [14]. However, none of the pulse compressing works were addressed in previous reports to obtain the femtosecond pulsewidth from such lasers. In this letter, we demonstrate for the first time the femtosecond soliton-pulse compression of the SOAFL, which is optically mode-locked by backward injecting a dark-optical-comb pulse train at repetition frequency of 10 GHz. Multistage linear dispersion compensation and nonlinear soliton compression results are performed. The effects of input power and pulsewidth on the compressing output are discussed.

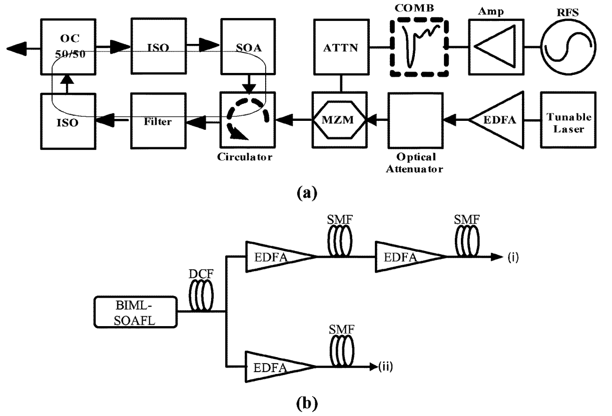

Fig. 1. (a) Schematic diagram of a backward optical injection-mode-locked SOAFL. ATT: attenuator. Amp: power amplifier. COMB: comb generator. ISO: optical isolator. OC: optical coupler. RFS: RF synthesizer. (b) Setup of (i) double-stage and (ii) single-stage soliton compression schemes.

II. EXPERIMENT

Fig. 1(a) illustrates the backward-optical-injection mode-locked SOAFL system with cavity length of 14 m, which consists of an SOAFL and an externally modulated distributed-feedback laser diode (DFBLD) source. The SOAFL is constructed by using a TWSOA, an optical circulator, two Faraday isolators, a tunable optical bandpass filter (OBPF), and an output coupler (OC) with a power-splitting ratio of 50%. The TWSOA exhibits a small signal gain of 15 dB at its peak wavelength of 1530 nm under a biasing current of 245 mA. A butterfly-packaged DFBLD (biased at 70 mA) operated at 25 °C and 1535 nm is employed to backward optical-inject the TWSOA. The DFBLD output was then externally modulated with a Mach–Zehnder intensity modulator (MZM) driven by an electrical comb generator (COMB) at 10 GHz. The COMB is operated at input power of 30 dBm by using a radio-frequency (RF) synthesizer (Rohde & Schwarz SML01) in connection

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Manuscript received August 23, 2005; revised February 9, 2006. This work was supported in part by the National Science Council of the Republic of China under Grant NSC 93-2215-E-009-007 and Grant NSC 94-2215-E-009-040.

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Digital Object Identifier 10.1109/LPT.2006.873515

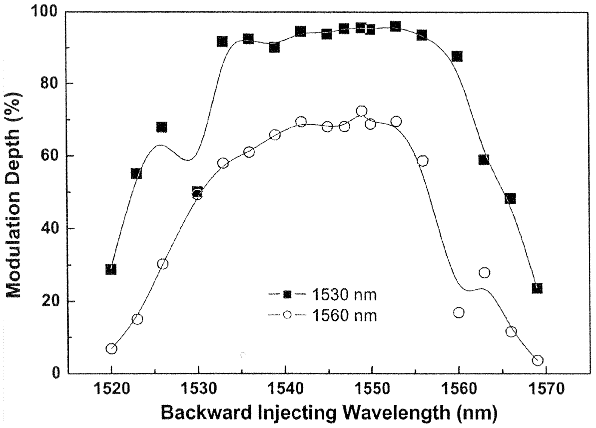

Fig. 2. XGM depth of signal at mode-locking wavelength of 1530 (solid line with solid square) and 1560 nm (dashed line with hollow circle) as a function of backward injecting wavelength.

with a power amplifier. By detuning the dc-bias level of the MZM from 5.2 to 0 V, the bright- and dark-optical-comb pulse trains with pulsewidth of ≤ 25 ps can be obtained at the MZM output, as illustrated in Fig. 2. The average powers of the bright- and dark-optical combs injected into the SOAFL are 0.44 and 2.5 mW, respectively. The dark-optical comb induces a nearly 100% gain-depletion modulation. In contrast, the bright-optical-comb injection leaves residual gain in the TWSOA.

III. Results and Discussion

The optimized mode-locking scheme is to operate the TWSOA at a high-gain condition and then gain-deplete the TWSOA via a high-power dark-optical comb with large duty cycle. Initially, the optimized adjustment between the backward injecting and the mode-locking wavelengths is performed to obtain a maximum XGM depth for optimizing the mode-locking of SOAFL. Under a constant dark-optical-comb power, the backward injected wavelength-depedent XGM depth of signal at 1530 nm can be greatly increased to $>90\%$ and is 40% larger than that of signal at 1560 nm (see Fig. 2). In other words, the backward injecting power required to deplete the SOAFL gain has to be increased at longer mode-locking wavelength. When operating the SOA at high-current condition, the gain spectrum of the SOA is blue-shifted by $\lambda_N = \lambda_0 - \kappa_0(N - N_0)$, where κ_0 is a constant, λ_N and λ_0 denote the peak wavelengths of the SOA gain spectrum at carrier densities of N (under backward injection) and N_0 (transparency), respectively [2]. The SOA changes from gain to loss condition ($N < N_0$) and leads to a red-shifted gain spectrum under an intense optical injection. This larger gain depletion as well as XGM depth occurs under the setting of mode-locking signal at shorter wavelengths and the backward optical injection at longer wavelengths.

The dark-optical-comb shown in Fig. 3(a) with duty-cycle and pulsewidth of $>94\%$ and 25 ps, respectively, is generated from an MZM driven by an electrical comb without dc offset, which results in the mode-locking of SOAFL with a shortest pulsewidth of 5.4 ps (measured by autocorrelation) at repetition frequency of 10 GHz, as shown in Fig. 3(b). Under an injecting power of 2.5 mW, the average output power of the optically mode-locked SOAFL is 130 μW, respectively. The lasing linewidth and time-bandwidth product (TBP) of the SOAFL pulse are 0.9 nm and 0.61, respectively. In contrast, the backward injection of a low-power bright-optical comb [see Fig. 3(c)] with short duty cycle (6%) only depletes the gain of the TWSOA in a relatively narrow duration, which leaves a large amount of residual gain in the TWSOA. Consequently, the backward bright-optical comb injection fails to induce sufficient modulation depth in the TWSOA for perfect mode-locking as shown in Fig. 3(d). The bright-optical-comb injection-mode-locked SOAFL reveals a tiny pulse train with an extremely large level of continuous-wave background, which is attributable to the insufficient gain-depletion of the TWSOA within one modulation period. Such a continuous-wave pedestal behind the mode-locked pulses can be eliminated by decreasing the gain of TWSOA. Although the output pulse obtained in our experiment is already the shortest one at repetition frequency of 10 GHz ever reported [14], [12], it is still constrained by several effects, such as the cavity-dispersion, the gain modulation and the negative chirp of the TWSOA in particular. The negatively chirped SOAFL pulse is subsequently compensated in a dispersion compensating fiber (DCF) spool with its length of 75 m. The linear chirp compensation also shortens the SOAFL pulsewidth from 5.4 to 3.9 ps without changing its spectral linewidth, as shown in Fig. 4(a) and (c). The TBP of DCF chirp compensated SOAFL pulse is reduced to 0.45.

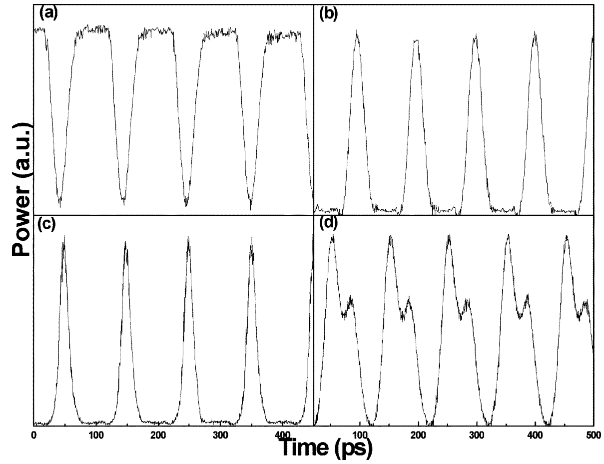

Fig. 3. Backward injected (a) dark-optical-comb and (b) bright-optical-comb pulse trains, and their corresponding mode-locked SOAFL pulse trains shown in (c) and (d), respectively.

Later on, multistage nonlinear soliton-pulse compression is employed to further shorten the SOAFL pulsewidth to femtosecond regime. In the first experiment, a double-stage single-mode-fiber (SMF)-based compressing geometry is considered. Previously, a similar work [15] which achieved the shortest pulsewidth of 180 fs at 1 GHz was demonstrated under an input peak power of 51 W. A lower peak power is obtained from the same EDFA as the repetition frequency of SOAFL pulse increases from 1 to 10 GHz, unless the input SOAFL pulsewidth at 10 GHz can be triply broader than that at 1 GHz to remain the same soliton compressing order (due to the proportionality of N to $(P_{\text{peak}} \cdot \tau)^{0.5}$. In this case, only the second-order soliton can be achieved under an input peak power of 11 W at 10 GHz, which requires an SMF length of

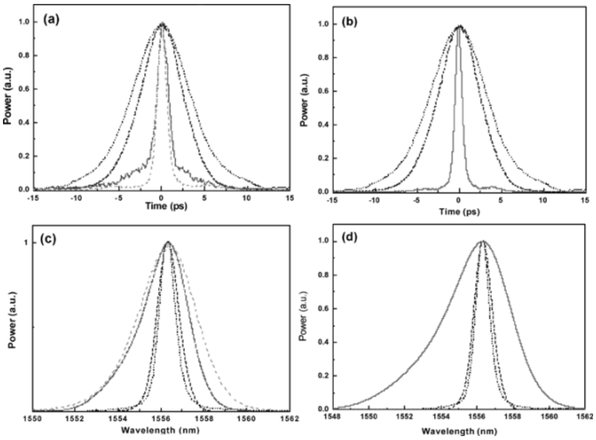

Fig. 4. Pulse shapes [(a) and (b)] and spectra [(c) and (d)] of the SOAFL after mode-locking (dotted curve), linear dispersion compression (dashed curve), first-stage (left figure, dashed–dotted curve), second-stage (left figure, short-dashed curve) soliton compressions, and single-stage soliton compressions (right figure, solid curve).

257 m. After the first-stage soliton compression, the SOAFL pulsewidth and linewidth become 760 ps and 2.5 nm, respectively, as shown in Fig. 4(a) and (c).

By employing a second-stage soliton compression with input peak power up to 42.5 W (amplified by a booster EDFA with average output power of 1.7 W at 10 GHz), the soliton pulse can further be shortened to 550 fs with a linewidth of 3.1 nm after propagating through an 80-m-long SMF spool. Note that the lower improvement on shortening the second-stage soliton pulsewidth is mainly attributed to the relatively short input pulsewidth, which inevitably constrain the soliton order. To overcome, a single-stage SMF-based soliton compressing experiment is performed. The generation of second-order soliton is capable under an input peak power of 42.5 W since the input SOAFL pulsewidth of 3.9 ps is much broader than 760 fs in previous experiment. The optimized SMF length to obtain the shortest compressed pulse for a second-order soliton is approximately equal to $0.245Z_0$ or 80 m, 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 Fig. 4(b) and (d), which exhibits a Sech^2-like pulsewidth of 410 fs and a spectral linewidth of 4.8 nm, providing a nearly transform-limit TBP of 0.25. The small TBP of the soliton-compressed SOAFL pulse is due to the use of a birefringent filter. The average power of the single-stage SMF-based soliton compressed SOAFL pulse is attenuated to 1.1 W, which corresponds to the peak power and pulse energy of >0.27 kW and 110 pJ, respectively. To date, this is already the shortest pulsewidth and highest output power ever obtained from the similar SOAFL systems at 10 GHz.

IV. CONCLUSION

By backward injecting the TWSOA with a dark-optical-comb of 94% duty-cycle and 25-ps dark-comb pulsewidth, an injection-mode-locked SOAFL is established with 5.4-ps pulsewidth at repetition frequency of 10 GHz. The negatively chirped SOAFL pulse can be linearly dispersion compensated and shortened to 3.9 ps by using a 75-m-long DCF, which is then nonlinearly soliton compressed to 410 fs in a single-stage SMF with length of 80 m. The double-stage pulse compression in SMF spools with input powers of 0.44 and 1.7 W at each stage only compresses the SOAFL pulsewidth to 760 and 550 fs, respectively. In contrast, the single-stage SMF shortens the 0.17-nJ SOAFL input pulse to 410 fs with a compressing ratio of up to 10. After compression, the lasing linewidth and TBP become 4.8 nm and 0.25, respectively. The maximum average output power is up to 1.1 W, corresponding to the peak power and pulse energy of >0.27 kW and 110 pJ, respectively.

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