1.2-ps mode-locked semiconductor optical amplifier fiber laser pulses generated by 60-ps backward dark-optical comb injection and soliton compression

Gong-Ru Lin*, I-Hsiang Chiu, and Ming-Chung Wu

**Department of Photonics & Institute of Electro-Optical Engineering, National Chiao Tung University*
1001 Ta Hsueh Road, Hsinchu 300, Taiwan, Republic of China
grlin@faculty.nctu.edu.tw

Abstract: Optically harmonic mode-locking of a semiconductor optical amplifier fiber laser (SOAFL) induced by backward injecting a dark-optical comb is demonstrated for the first time. The dark-optical comb with 60-ps pulsewidth is generated from a Mach-Zehnder modulator, which is driven by an electrical comb at a DC offset of $0.3V_{\pi}$. Theoretical simulation indicates that the backward injection of dark-optical comb results in a narrow gain window of 60 ps within one modulating period, providing a cross-gain-modulation induced mode-locking in the SOAFL with a shortest pulsewidth of 15 ps at repetition frequency of 1 GHz. The mode-locked SOAFL pulsewidth can be slightly shortened to 10.8 ps with a 200m-long dispersion compensating fiber. After nonlinearly soliton compression in a 5km-long single mode fiber, the pulsewidth, linewidth and time-bandwidth product become 1.2 ps, 2.06 nm and 0.31, respectively.

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

References and links

1. D. M. Patrick, "Modelocked ring laser using nonlinearity in a semiconductor laser amplifier," Electron. Lett. **30**, 43-44 (1994).
2. T. Papakyriakopoulos, K. Vlachos, A. Hatziefremidis, and H. Avramopoulos, "20-GHz broadly tunable and stable mode-locked semiconductor amplifier fiber ring laser," Opt. Lett. **24**, 1209-1211 (1999).
3. 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. **33**, 1630-1632 (1997).
4. 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. **36**, 1580-1581 (2000).
5. L. Schares, L. Occhi, and G. Guekos, "Picosecond wavelength tunable SOA-based laser sources at 10-40 GHz repetition rates," Conference on Lasers and Electro-Optics, Technical Digest, (Optical Society of America, Long Beach MD, 2002), CML3., 56-57.
6. G.-R. Lin, Y.-S. Liao, and G.-Q. Xia, "Dynamics of Optical Backward Injection Induced Gain-Depletion Modulation and Mode-Locking of Semiconductor Optical Amplifier Fiber Laser," Opt. Express **12**, 2017-2025 (2004).
7. 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. **11,** 521-523 (1999).
8. J. He and K. T. Chan, "All-optical actively modelocked fibre ring laser based on cross-gain modulation in SOA," Electron. Lett. **38**, 1504-1505 (2002).
9. G. P. Agrawal, *Nonlinear Fiber Optics*. (Academic New York, 1989).
10. 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. **18**, 1080-1082 (1993).
11. L. E. Nelson, S. B. Fleischer, G. Lenz, and E. P. Ippen, "Efficient frequency doubling of a femtosecond fiber laser," Opt. Lett. **21**, 1759-1761 (1996).
12. 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. **31**, 195-196 (1995).

#6203 - $15.00 US Received 5 January 2005; revised 30 January 2005; accepted 31 January 2005

1. Introduction

Backward optical injection is a novel technology to achieve mode-locking in semiconductor optical amplifier based fiber-ring lasers (SOAFLs) [1-8]. The backward optical injection induced periodical gain-depletion as well as cross-gain modulation (XGM) in a SOAFL has been experimentally demonstrated and theoretically discussed [4-6]. Previously, a 4.3-ps pulse was obtained by gain-depleting the SOAFL with a compressed laser diode pulse-train at repetition of 20 GHz [2]. Similar experiments demonstrated at a higher repetition rate up to 40 GHz, a shorter pulsewidth of 1.9 ps and a wider wavelength tuning range of about 20 nm [3-5]. 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. In this paper, we demonstrate for the first time the comparison on optical harmonic mode-locking of a SOAFL via backward injection of optical comb-like bright and dark pulse-trains (referred hereafter as bright- and dark-optical combs) with a pulsewidth of 60 ps at repetition frequency of 1 GHz. The differences in mode-locked pulsewidth and pulse shape between two opposite modulation schemes are also interpreted, and the correlation between the gain-depletion time and mode-locking pulsewidth is discussed. To further shorten the SOAFL pulsewidth, the fiber-based linear dispersion compensation and nonlinear soliton compression techniques are also reported.

2. Experimental setup and principle of operation

Figure 1 illustrates the backward-optical-injection mode-locked SOAFL system with cavity length of 14 m, which consists of one traveling-wave typed SOA at 1530 nm, an optical circulator, a faraday isolator, an optical tunable bandpass filter (OBPF), and an output coupler (OC) with a power-splitting ratio of 50%.

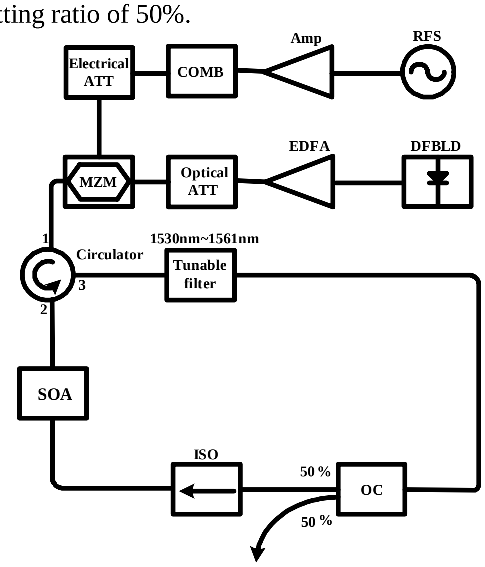

Fig. 1 The schematic diagram of the backward-optical- injection mode-locked SOAFL. ATT: attenuator; Amp: power amplifier; COMB: comb generator; DFBLD: distributed feedback laser diode. EDFA: erbium-doped fiber amplifier; ISO: optical isolator; OC: optical coupler; SOA: semiconductor optical amplifier; RFS: RF synthesizer.

The SOA was DC-biased at 225 mA (well above threshold current of 50 mA). To backward optical-inject the SOA for harmonic mode-locking, a butterfly-packaged distributed feedback laser diode (DFBLD, biased at 70 mA) operated at 1535 nm and 25^{o}C was amplified

#6203 - $15.00 US Received 5 January 2005; revised 30 January 2005; accepted 31 January 2005

by a 20dB-gain erbium-doped fiber amplifier (EDFA), and externally modulated by a Mach-Zehnder intensity modulator (MZM) driven with an electrical comb generator (COMB). The COMB is operated at input power of 29 dBm by using an RF synthesizer (Rohde & Schwarz SML01) in connection with a power amplifier of 40-dB gain. By changing the DC-bias level of the MZM at $1.2V_\pi$ and $0.3V_\pi$, the bright- and dark-optical combs with pulsewidth of ≤60 ps can be obtained at the MZM output, as illustrated in Fig. 2.

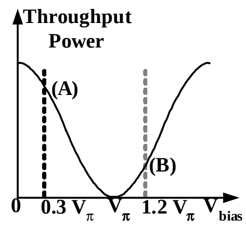

Fig. 2 The driving points of Mach-Zehnder modulator for (A) dark- and (B) bright-optical combs.

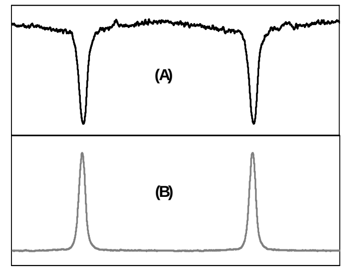

Fig. 3 The (A) dark- and (B) bright-optical combs.

The average powers of the bright- and dark-optical combs (see Fig. 3) injected into the SOAFL are 0.61 mW and 4.46 mW, respectively. The dark-optical comb is backward injected into the SOAFL via the optical circulator, which then induces a gain-depletion modulation depth of nearly 100% under fine adjustment of the SOA driving current. In contrast, the bright-optical-comb injected SOAFL leaves much residual gain in the SOA. The use of the isolator and OBPF ensure unidirectional propagation and avoid the lasing of the injected optical-comb in the SOAFL. The harmonic mode-locking is achieved when the repetition frequency of the injected dark-optical comb exactly coincides with one harmonic longitudinal-mode frequency of the SOAFL.

3. Results and discussion

3.1. Backward injection of the comb-like dark pulse-train into SOA

With the backward injection of the dark-optical comb, the central wavelength and output power of the harmonic mode-locked SOAFL are 1530.24 nm and 26.78 μW, respectively. The mode-locked SOAFL pulsewidth significantly shrinks from 68 ps to 15 ps at a repetition frequency of 1 GHz (measured by an auto-correlator after de-convolution) as the average power of the dark-optical comb increases from 1.3 to 4.5 mW, which is already the shortest pulsewidth ever reported in similar systems at repetition rate of 1 GHz. The dark-optical comb injection-mode-locked SOAFL pulse shape is shown in Fig. 4(b). 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. However, the excess injecting power (up to 6.46 mW) oppositely leads to a pulse broadening due to the decrease in gain and modulation depth of the SOA. 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 a huge continuous-wave component in the SOAFL output.

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. 4(a). This eventually results in a perfect mode-locking pulse-train with peak power of 3.46 mW, as shown in Fig. 4 (b). In comparison, the backward injection of a low-power bright-optical comb (see Fig. 4(c)) with short pulsewidth only depletes the gain of the SOA in a relatively narrow duration, which leaves a large amount of residual gain in the SOA. Consequently, the backward bright-optical comb injection fails to induce sufficient modulation depth δ in the SOA for perfect mode-locking as shown in Fig. 4(d). The mode-locked pulse is generated from the SOAFL, but associated with a long pedestal in the falling part. Such a continuous-wave pedestal behind the mode-locked pulses cannot be eliminated even by optimizing all of the other system parameters (except the decreasing in gain of SOA). The determination of the minimum gain-depletion width required for mode-locking the SOAFL was previously demonstrated, which clearly interpreted that a backward pulsed injection with duty cycle of <30 % contributes less to the initiation of harmonic mode-locking in the SOAFL [6]. Both the larger gain-depletion (modulation) depth and the narrower gain width of the SOA are mandatory to the build-up of the mode-locking in SOAFL.

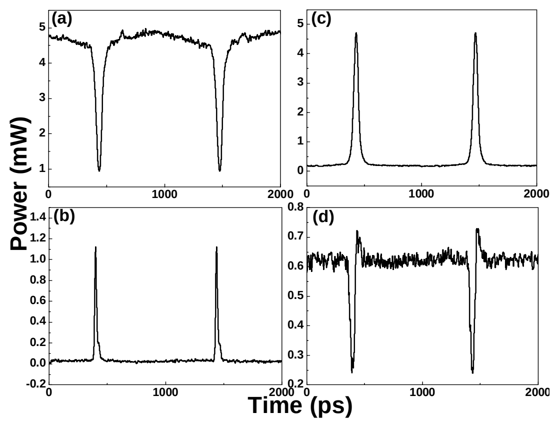

Fig. 4. The backward optical injected (a) dark and (b) bright-optical combs, and their corresponding mode-locked SOAFL pulse-trains are shown in (c) and (d), respectively.

3.2. Comparison of SOAFL pulses mode-locked by comb-like dark and bright- pulse-train modulated SOA

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. 5. 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,[10] 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.

#6203 - $15.00 US Received 5 January 2005; revised 30 January 2005; accepted 31 January 2005

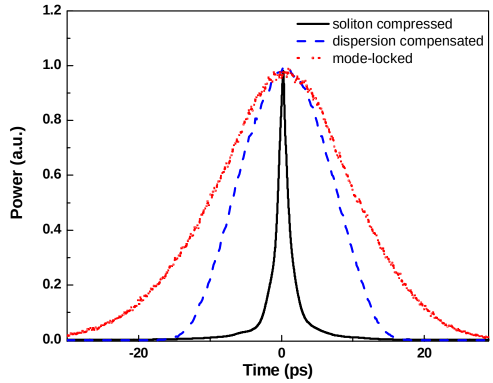

Fig. 5 Comparison of SOAFL pulse shapes after mode-locking (dotted curve), linear dispersion compression (dashed curve) and nonlinear soliton compression (solid curve).

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 1.2 ps after propagating through a 5km-long SMF (D~16 ps/nm·km). The lasing spectra of the mode-locked SOAFL after propagating through the DCF and SMF are plotted in Fig. 6. 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.

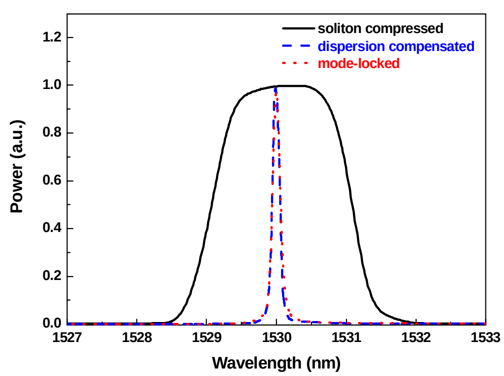

Fig. 6 Lasing spectra of dark-optical comb mode-locked SOAFL pulse before (dotted curve) and after propagating through a 200-m DCF (dashed curve) and a 5-km SMF (solid curve).

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

#6203 - $15.00 US
Received 5 January 2005; revised 30 January 2005; accepted 31 January 2005

phenomenon, as shown in Fig. 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 [12]. 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.

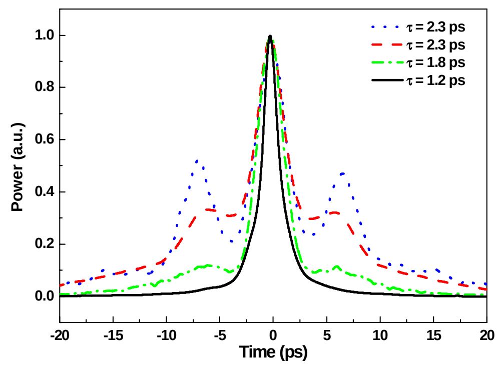

Fig. 7 The suppression of polarization-mode dispersion induced side-lobe in the auto-correlated trace of the backward optical-comb injection-mode-locked SOAFL pulse shapes. Dotted curve: the amplified mode-locked pulse shape after propagating through SMF. Dashed curve: partially controlled polarization 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.

Previously, Patrick *et al.* have 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 [1]. He and Chan also reported a pulsewidth of 21 ps at 5 GHz from a wavelength-tuneable cross-gain-modulated SOAFL [8]. 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 [2]. 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 [3]. 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 [6]. 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 [7]. 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 [7]. With a soliton pulse-compression technique, the SOAFL has shown to exhibit the shortest and nearly transform-limited pulsewidth to date.

#6203 - $15.00 US Received 5 January 2005; revised 30 January 2005; accepted 31 January 2005

4. Conclusions

In conclusion, the dark-optical comb injection-mode-locked SOAFL pulse can further be compressed to 1.2 ps 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 60-ps pulsewidth can be generated using a Mach-Zehnder intensity modulator (MZM) at biased point of $0.3V_{\pi}$. 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 ≤60 ps) within one modulation period, providing a cross-gain-modulation induced mode-locking of the SOAFL with a shortest pulsewidth of 15 ps at repetition frequency for 1 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 200m-long DCF and a 5km-long SMF, the pulsewidth of the mode-locked SOAFL can be linearly dispersion-compensated to 10.8 ps and nonlinearly soliton-compressed to 1.2 ps, respectively. The lasing linewidth and time-bandwidth product of such a dark-optical comb mode-locked SOAFL after compression are 2.06 nm and 0.31, respectively.

Acknowledgments

The authors thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under NSC 93-2215-E-009-007.