All-optical pulse generation based on gain-induced four-wave mixing in a semiconductor optical amplifier

Fangxin Li* and Amr S. Helmy

Department of Electrical and Computer Engineering, University of Toronto, Toronto M5S 3G4, Canada
**Corresponding author: fangxinlee.li@utoronto.ca*

Received February 6, 2013; revised March 7, 2013; accepted March 7, 2013; posted March 7, 2013 (Doc. ID 184975); published April 3, 2013

A simple all-optical pulse generation technique based on gain-induced four-wave mixing in a semiconductor optical amplifier is introduced. The introduced concept is theoretically investigated and experimentally demonstrated. For a concept demonstration, 10 GHz and 42.5 GHz pulse trains are generated. A 20 nm central wavelength tunability is achieved. © 2013 Optical Society of America
OCIS codes: 190.4390, 190.4223.

High-repetition-rate optical clocks play a crucial role in many fields, including telecommunication system, THz generation, and metrology [1]. Several technologies have been explored to generate actively mode-locked pulse trains with an electronically driven active medium in the ring cavity. These include photonic crystal fibers [2], electroabsorption modulators [3], lithium niobate modulators [4], or their combinations [5]. However, the pulse repetition rate is usually limited by the bandwidth of the intracavity modulator. To mitigate this limitation, filtering of highly stable low-repetition-rate optical combs utilizing cavities such as Fabry–Perot etalons can be used [6]. This scheme is not flexible as it requires highly precise control of ultrahigh finesse etalons, which limits the repetition rate to the free spectral range of the filter.

Optical pulse sources based on semiconductor technology offer many advantages, including large gain bandwidth, high small signal gain, rapid tunability, long-term stability, mass production, and large-scale integration, which are important for cost and scalability [7]. Semiconductor optical amplifiers (SOAs) can serve as a modulator in the cavity of a fiber ring laser based on cross-gain modulation [8] or cross-phase modulation [9] from an external injection. However, the bandwidth of external injection often limits the repetition rate of the generated pulses. To generate high repetition rate, rational harmonic mode-locking technology is used. This kind of technology introduces different amplitude among pulses, thus needs amplitude equalization, which limits its practical use [7]. In order to achieve high repetition rate with continuous tunability, generating pulse from dual-frequency beating signals using four-wave mixing (FWM) is also demonstrated for high-repetition-rate optical clock [10,11]. However, to suppress the stimulated Brillouin scattering, which dominates when using narrow linewidth lasers, additional external modulation or broadband source is required [10], thus requiring a much more complicated setup. Moreover, the operating wavelength is limited to tunability of the source laser.

In this work, we introduce a novel, simple method to generate optical clock with wavelength tunability. Specifically, two continuous wave (CW) lasers are injected into a conventional SOAs-based fiber ring laser. The beating signal generated by these two lasers causes the modulation of the SOA gain saturation inside the cavity. Thus, the SOA will function as the gain medium as well as the active modulation medium. As a result, when the lasing mode inside the cavity [controlled by the bandpass filter (BPF)] is amplified, it also results in gain-induced FWM. The proposed technique is particularly versatile in comparison to its counterparts; the repetition rate is controlled by the frequency difference between the two CW light sources, overcoming the bandwidth limitation of other techniques, which require an RF source. In addition, the operating wavelength is tuned by sweeping the central wavelength of the BPF. Moreover, this new technique is cost-effective and provides the possibility for hybrid integration as it is comprised of semiconductor chips that can be heterogeneously integrated on an Si platform. For a concept demonstration, pulse train with repetition rate up to 42.5 GHz is generated. A 20 nm central wavelength tunability is achieved in this first demonstration.

The initial beating signal was obtained by simultaneous injection of two linearly polarized continuous waves with different frequencies and equal powers into the SOA-based fiber ring cavity. To fully understand the effect of the injected signal on the gain depletion and mode-locking performance of the laser, the pulse evolution of the mode-locked laser is first theoretically investigated. The numerical simulations were performed by solving the coupled equations of the field evolution $p(z,t)$ inside the semiconductor amplifier:

$$\frac{\partial p(z,t)}{\partial z} + \frac{n_{\mathrm{soa}}}{C}\frac{\partial p(z,t)}{\partial t} + i\frac{\beta_{2\mathrm{soa}}}{2}\frac{\partial^2 p(z,t)}{\partial t^2} + i\gamma|p(z,t)|^2 p(z,t) = \Gamma[g(N(z,t)) - \alpha_{\mathrm{int}}]p(z,t), \quad (1)$$

where n_{soa} and $\beta_{2\mathrm{soa}}$ are the group indices and second-order dispersion of the SOA, $\gamma = \omega_0 n_2/cA$ is the Kerr nonlinear coefficient in the SOA. Γ is mode confinement factor and α_{int} is the internal loss of SOA. The time-dependent carrier density $N(z,t)$ and gain $g(N(z,t))$ inside the SOA are described by the following rate equations:

$$\frac{\partial N(z,t)}{\partial t} = \frac{I}{qV} - \frac{N(z,t)}{\tau_c} - \sum \frac{g_{\mathrm{inj}}(z,t)}{h\omega_i A}\overline{P_{\mathrm{inj}}(z,t)} - \frac{g(z,t)}{h\omega_0 A}\overline{P(z,t)}, \quad (2)$$

 © 2013 Optical Society of America

$$g(N(z,t)) = a_1[N(z,t) - N_0] - a_2[\lambda - \lambda_N]^2 + a_3[\lambda - \lambda_N]^3, \quad (3)$$

where I, A, and V denote the injection current, cross-section area in the active area, and volume of the SOA; q is the electron charge. N_0 represents the transparent carrier density, $\lambda_N = \lambda_0 - a_4(N - N_0)$ is the corresponding wavelength for peak gain, a_1 denotes the differential gain coefficient, a_2 and a_3 are constant, which characterize the width and asymmetry of the gain profile. a_4 is the empirical constant describing the shift of the gain peak. τ_c denotes the spontaneous emission life time. To fully simulate the laser operation, all equations must be supplemented by the boundary condition:

$$P(\omega, z = 0) = \sqrt{\eta(1 - \alpha_{\mathrm{cav}})}H(\omega)\exp[-j\beta(\omega)L]P(\omega, z = L), \quad (4)$$

where η is the power coupling percentage, α_{cav} the cavity losses, $\beta(\omega)$ the propagation constant (expanded to the second-order dispersion term), and L the length of the cavity. $P(\omega, z)$ denotes the Fourier transform of $p(z,t)$ and $H(\omega)$ is the transfer function of the BPF.

The operation of the proposed source was first confirmed by simulating the 10 GHz pulse generation by use of a split-step Fourier method. The 10 GHz beating signal is simulated by fixing central wavelength of two CW lasers at 1550 and 1550.08 nm. The parameters of the SOA are, $\alpha_{\mathrm{int}} = 20\ \mathrm{cm}^{-1}$, $L_{\mathrm{soa}} = 500\ \mu\mathrm{m}$, $A = 0.4\ \mu\mathrm{m}^2$, $\Gamma = 0.3$, $a_1 = 2.5 \times 10^{20}\ \mathrm{m}^2$, $a_2 = 7.4 \times 10^{18}\ \mathrm{m}^{-3}$, $n_{\mathrm{soa}} = 3.56$, $a_3 = 3.16 \times 10^{25}\ \mathrm{m}^{-4}$, $\tau_c = 300$ ps, $a_4 = 3 \times 10^{-32}\ \mathrm{m}^4$, $\beta_{2\mathrm{soa}} = 0.05\ \mathrm{ps}^2/\mathrm{cm}$, $I = 600$ mA, and $n_2 = -1\ \mathrm{cm}^2\ \mathrm{GW}^{-1}$. The parameters for the boundary condition are $L = 6.2$ m, $\beta_2 = 1\ \mathrm{ps}^2/\mathrm{km}$, $\eta = 0.9$, and $\alpha_{\mathrm{cav}} = 6$ dB. The transfer function of the BPF is assumed to be a Gaussian profile with 5 nm FWHM bandwidth. Figure 1(a) shows the temporal profile and corresponding spectrum of generated 10 GHz pulse trace separately. After 30 round trips, the pulse has stabilized at a width of ~8 ps FWHM and the pulse peak power is ~14 mW. The repetition rate tunability is simulated by fixing central wavelength of one CW laser at ~1550 nm and tuning the central wavelength of another CW laser. When it is tuned to ~1550.32 and ~1555.8 nm, the difference corresponds to ~40 and ~100 GHz repetition rates. Figures 1(b) and 1(c) present the temporal profiles and spectra of the generated pulses for the repetition rates 40 and 100 GHz. It is clear that the generated pulse trains exhibit the same repetition rate as the beating frequency of the external signal. The generated 10, 40, and 100 GHz pulses are chirped. The estimated time-bandwidth product (FWHM) is approximately 0.58. It is worth noting that the intensity of the two inject CW lasers is increased with increasing the repetition rate to optimize the laser operation. In order to generate the pulse rates discussed, the intensity of the CW lasers in our simulation is ~3 mW for 10 GHz, ~6 mW for 40 GHz, and ~10 mW for 100 GHz.

Figure 2 is the experimental setup of the proposed source. The main fiber ring cavity is comprised of two SOAs (Thorlab BOA): the first SOA functions as the gain and modulation medium, while the second one changes the net gain of the cavity. The SOA has a typical small signal gain of 30 dB at 600 mA current bias with an associated saturation output power of 17 dBm. Each SOA is mounted on a thermoelectric cooler to stabilize the performance of the SOA. The tunable optical bandpass filter (OBPF) has a 3 dB bandwidth of ~2 nm and a 20 nm tuning range. It is employed to perform wavelength selection to tune the central wavelength of the output and filter the injected beating signal. The isolator ensures the unidirectional propagation of light. The polarization controller sets the appropriate polarization state as the SOA gain is birefringent. The length of the main cavity is ~15.5 m, which results in a fundamental cavity resonance frequency of 12.5 MHz. To get stable harmonic mode locking at 10 GHz to 42.5 GHz, the cavity length is first calibrated by mode locking the fiber laser through the injection of a 0.5 GHz pulse source. Two linearly polarized single-mode distributed feedback (DFB) lasers are injected into the ring laser to modulate the SOA gain. The central wavelength of the DFBs is ~1551 nm and can be tuned using a temperature controller.

The source first operates in CW mode (i.e., without external injection) and the central wavelength of output CW light is tuned from 1545 to 1565 nm with almost constant 4.3 dBm output power across its tuning span. By fine tuning one DFB central wavelength to 1551.23 nm and fixing another DFB at 1550.89 nm, a 42.5 GHz beating signal is generated. When the external beating signal with the power of 10 dBm is coupled into the cavity, the ring laser source runs in a stable mode-locked operation at 42.5 GHz with 2.88 dBm output power, which is slightly lower than that in CW mode. Figure 3(a) shows the corresponding optical spectrum of the pulse train and the

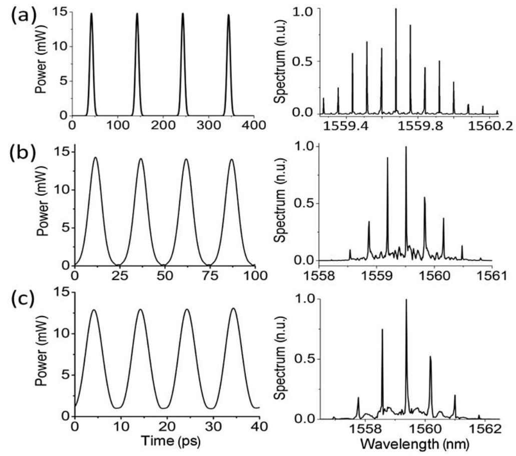

Fig. 1. Temporal profile (left plot) and corresponding spectrum (right plot) of generated (a) 10 GHz, (b) 40 GHz, and (c) 100 GHz pulse trace separately.

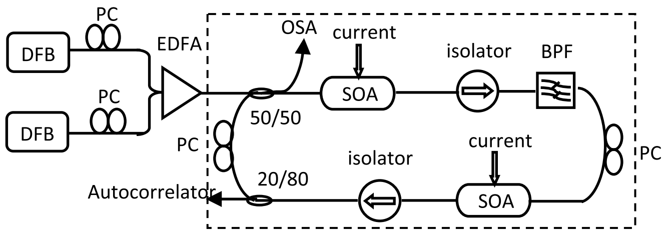

Fig. 2. Experimental setup for pulse high repetition rate laser setup based gain-induce FWM. PC, polarization controller; EDFA, erbium-doped fiber amplifier

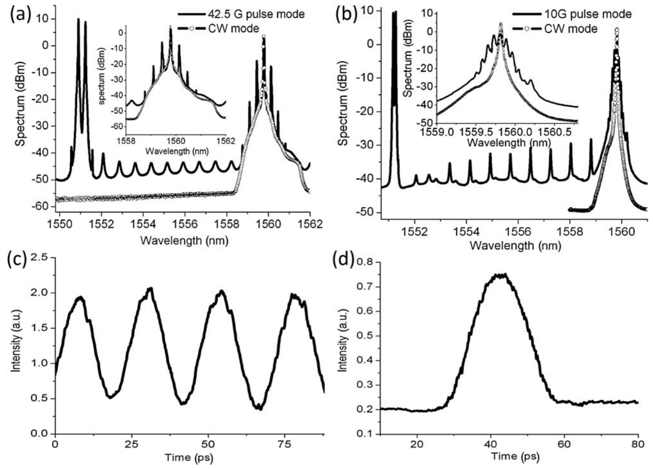

Fig. 3. Measured profiles of spectrum characteristics of the output (a) 42.5 GHz and (b) 10 GHz pulse train with two CW inputs (solid line) and the output spectrum when the laser operates in CW mode (dashed line). Inset: zoomed spectrum. (c), (d) Autocorrelation trace of the output of (c) 42.5 GHz and (d) 10 GHz pulse train.

CW output spectrum. Figure 3(c) shows autocorrelation trace of the 42.5 GHz pulse train. The central wavelength of the output laser is ~1559.8 nm and it has ~11 ps FWHM pulse width. The DFB central wavelength is then shifted to 1550.99 nm to generate 10 GHz pulse train with 17 ps pulse width. The spectrum and the autocorrelation trace are shown in Figs. 3(b) and 3(d). In order to compress the noise inside the cavity, a 0.35 nm FWHM BPF is used for the 10 GHz pulse generation. For both 10 GHz and 42.5 GHz beat frequencies the estimated time-bandwidth products are approximately 0.65, indicating that the output pulse is not transform-limited but chirped. The experimentally generated pulse exhibits broader pulse width than the simulation. This is due to the fact that the BPF inside the cavity has smaller bandwidth and the SOA has less nonlinearity. The repetition rate of the proposed technique is currently limited by the FWM efficiency and the saturation power of the used SOAs. Frequency comb generation of up to 15 nm has been demonstrated using ultralong SOAs with a high FWM efficiency [11]. By replacing SOA with ultralong SOAs and by managing the overall cavity dispersion the repetition rate should easily exceed 100 GHz.

In order to investigate the wavelength tunability of the proposed technique, we changed the central wavelength of the OBPF. Figure 4(a) shows the wavelength tunability of the actively mode-locked pulse laser. A 20 nm wavelength tuning span is achieved, limited by the wavelength tunability of the BPF. Theoretically, the tuning range can cover the entire gain bandwidth of the SOA using this technique. It is found the laser exhibits slightly narrow pulse width when it operates close to the central wavelength of external injection. SOA shows a higher amplified spontaneous emission noise at longer wavelength, which leads to a broadening pulse width with longer operation wavelength. Figure 4(b) shows the relation between the pulse shape and the CW input powers. The shorter pulses can be obtained by increasing the input power of the CW lasers. This is because the stronger external injection will cause a deeper gain modulation, thus resulting in a narrow pulse width.

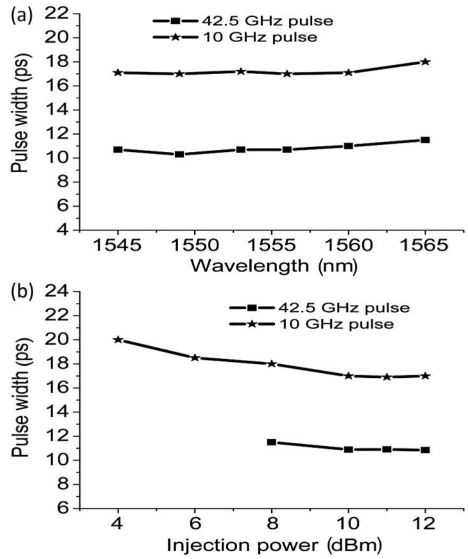

Fig. 4. (a) Pulse characteristics versus the central wavelength of the OBPF. (b) Pulse characteristics versus the input power of external pulse.

In conclusion, a novel and simple actively mode-locked SOA-based fiber ring laser with an external injection is presented in this Letter. Up to 42.5 GHz pulse train is generated. A 20 nm wavelength tuning span is achieved. The unique features of this technique are: wide-tuning of the repetition rate, broad wavelength tuning range with nearly constant pulse width and output power as well as no need for complex RF circuitry. These features render this technique a very attractive candidate for many applications. These include hybrid optical clocks, sources for time/wavelength division multiplexing, and as a characterization source for passive/active photonics devices.

References

1. U. Keller, Nature **424**, 831 (2003).
2. L. He, B. Yang, X. Song, X. Zhang, and L. Yu, Chin. Opt. Lett. **4**, 342 (2006).
3. L. Xu, L. F. K. Lui, P. K. A. Wai, H. Y. Tam, and C. Lu, in *National Fiber Optic Engineers Conference*, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper JThA10.
4. C. Wu and N. K. Dutta, IEEE J. Quantum Electron. **36**, 145 (2000).
5. L. Duan, C. J. K. Richardson, Z. Hu, M. Dagenais, and J. Goldhar, IEEE Photon. Technol. Lett. **14**, 840 (2002).
6. Z. Jiao, J. Liu, S. Lu, X. Zhang, P. J. Poole, P. J. Barrios, and D. Poitras, IEEE Photon. Technol. Lett. **23**, 543 (2011).
7. K. Vlachos, C. Bintjas, N. Pleros, and H. Avramopoulos, IEEE J. Sel. Top. Quantum Electron. **10**, 147 (2004).
8. T. Papakyriakopoulos, K. Vlachos, A. Hatziefremidis, and H. Avramopoulos, Opt. Lett. **24**, 1209 (1999).
9. L. Schares, R. Paschotta, L. Occhi, and G. Guekos, J. Lightwave Technol. **22**, 859 (2004).
10. S. Pitois, J. Fatime, and G. Millot, Opt. Lett. **27**, 1729 (2002).
11. P. Runge, C. Bunger, K. Petermann, M. Schlak, W. Brinker, and B. Sartorius, J. Lightwave Technol. **28**, 754 (2010).