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Numerical study of a harmonic mode-locked semiconductor optical amplifier fiber ring laser

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Abstract

An improved harmonic mode-locked Semiconductor optical amplifier (SOA) fiber ring lasers has been presented and numerically investigated based on the self-reproduction theory. The numerical result shows that a narrower optical pulse train with a more symmetrical-temporal shape can be obtained, when the modulation SOA is DC biased on high current, whereas the gain SOA is DC biased on the low current functions as a gain compensator in the experimental setup. Also, the system parameters effects on the characteristic of the harmonic mode-locked pulse have been investigated.

Keywords: Laser technique; Fiber laser; Harmonic mode locking; Semiconductor optical amplifier; Cross-gain modulation

1. Introduction

Optical signal sources that are capable of generating wavelength tunable ultra-short pulse train with high quality and high repetition rates play an important role in the optical networks that may combine wavelength division multiplexing (WDM) and optical time domain multiplexing (OTDM) transmission techniques. Actively mode-locked fiber laser due to being capable of generating ultra-short transform-limited optical pulse train has attracted people's especial research interest [1–4]. However, the pulse output from the actively mode-locked fiber laser is inherently unstable because of the fluctuations of polarization state and cavity-length drift caused by mechanical vibration and thermal fluctuations. Semiconductor optical amplifier (SOA), due to having some advantages such as rapid response, high stability and polarization independence, has been used in fiber laser. SOA acted as the gain medium compared with erbium-doped fiber amplifier (EDFA) can suppress pulse-amplitude fluctuation and super-mode noise [5,6], and an all-optical modulation SOA can also act as a mode locker [7,8]. So, a novel model of backward-optical-injection harmonic mode-locked fiber ring laser consisting of two SOAs has been proposed and preliminary experimental and theoretical results have been reported [9,10]. In this experimentation, the first SOA (called as the modulation SOA), which is DC biased slightly above threshold is backward injected by the sinusoidal-wave-modulated distributed-feedback laser diode (DFBLD), functions as an optically controlled

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loss modulator, whereas the second SOA (called as the gain SOA), which is DC biased on the high current, is employed to offer constant gain without any modulation. The farther research found that this experimental setup can also work on the contrary condition, namely, the modulation SOA is DC biased on the high current, whereas the gain SOA is DC biased on the low current functions as a gain compensator, and the quality of the output mode-locked pulse was distinctly improved on the new condition.

2. Theoretical model

The schematic diagram of the harmonic mode-locked SOA fiber ring laser [9,10] is shown in Fig. 1. A modulated optical signal provided by a gain-switch DFBLD passes through an optical circulator, then injects into the modulation SOA, the gain SOA functions as gain compensator provides the necessary gain, and two Faraday optical isolators ensure a unidirectional propagation. In order to obtain the harmonic mode-locked pulses, the frequency (f_m) of the modulated optical signal should be nearly integer times of the cavity fundamental frequency (f_c), that is to say, $f_\mathrm{m} = nf_\mathrm{c}$ (n is a positive integer). So the nth-order harmonic mode-locked pulse series, whose repetition rate (f_r) is the same as the modulating frequency, is output from optical coupler with a power-splitting ratio of 95:5.

In this paper, a traveling-wave rate-equation model [9,10] is adopted to simulate the mode-locked pulse shape and the counterclockwise parts of the traveling-wave equations are neglected because of the existence of the Faraday optical isolators. In general, when the pulse

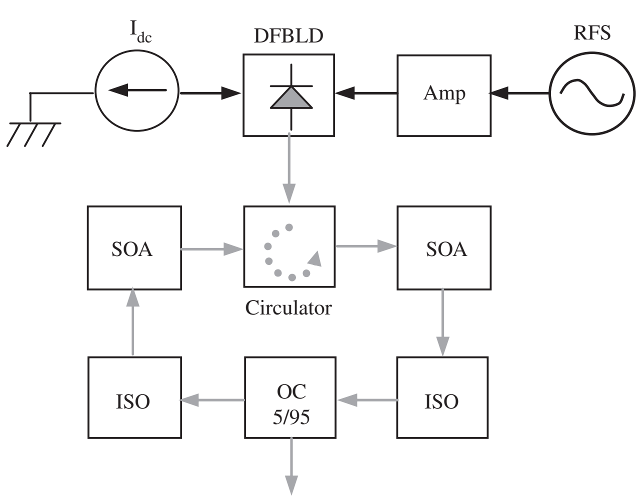

Fig. 1. Schematic diagram of the harmonic mode-locked SOA fiber ring laser: RFS, RF synthesizer; Amp, power amplifier; ISO, optical isolator; Circulator, optical circulator; OC, optical coupler.

train passes through a SOA, the carrier density in the cavity will vary with both time and space. In order to describe accurately the propagation characteristics of pulse in SOA, the SOA is spliced into 20 sections in the simulation. The gain depletion effects induced by the mode-locked pulse and the backward-optical-injection signal in the modulation SOA, and the asymmetric gain of the SOA have been taken into consideration. The differential rate equations for the carrier density in the jth section of the modulation SOA, and the propagation equations that describe the time-varied powers of the mode-locked signal pulse and the modulation signal in the modulation SOA, can be written as

$$\frac{\partial N_j(z,T)}{\partial T} = \frac{I}{qV} - \frac{N_j(z,T)}{\tau_\mathrm{c}} - \left[\frac{\Gamma g_{\mathrm{m},j}(z,T)}{h\upsilon_\mathrm{m} A_\mathrm{cross}}\overline{P_{\mathrm{m},j}} + \frac{\Gamma g_{\mathrm{l},j}(z,T)}{h\upsilon_\mathrm{l} A_\mathrm{cross}}\overline{P_{\mathrm{l},j}}\right], \quad (1)$$

$$\frac{\partial P_{\mathrm{m},j}(z,T)}{\partial z} = -\left[\Gamma g_{\mathrm{m},j}(z,T) - \alpha_\mathrm{int}\right] P_{\mathrm{m},j}(z,T), \quad (2)$$

$$\frac{\partial P_{\mathrm{l},j}(z,T)}{\partial z} = \left[\Gamma g_{\mathrm{l},j}(z,T) - \alpha_\mathrm{int}\right] P_{l,j}(z,T), \quad (3)$$

where the subscripts m and l denote the parameters of modulated and mode-locked signal, respectively, N_j is the carrier density in the jth section of the SOA, T ($= t - z/v_\mathrm{g}$, where v_g is the group velocity in the SOA) represents the time in a reference frame moving along with the pulse, I is the injection current, V is the volume of the SOA, q denotes the electron charge, $h\upsilon$ is the photon energy, Γ is the confinement factor, A_cross represents the cross-sectional area of the active layer in the SOA. The carrier lifetime is defined as $\tau_\mathrm{c}^{-1} = A + BN + CN^2$, where A, B and C represent the non-radiative recombination, the spontaneous emission and the Auger recombination process, respectively, α_int is the internal loss of the SOA, $\overline{P_{\mathrm{m},j}}$ and $\overline{P_{\mathrm{l},j}}$ are the average powers of modulation and mode-locked signal in the jth section of the SOA, respectively, and can be expressed by

$$\overline{P_{\mathrm{m},j}} = \frac{1}{-\Delta L}\int_0^{-\Delta L} P_{\mathrm{m},j+1} \exp\{-[\Gamma g_{\mathrm{m},j}(N_j) - \alpha_\mathrm{int}]z\}\,\mathrm{d}z, \\ = \frac{\exp\{[\Gamma g_{\mathrm{m},j}(N_j) - \alpha_\mathrm{int}]\Delta L\} - 1}{[\Gamma g_{\mathrm{m},j}(N_j) - \alpha_\mathrm{int}]\Delta L} P_{\mathrm{m},j+1}, \quad (4)$$

$$\overline{P_{\mathrm{l},j}} = \frac{1}{\Delta L}\int_{(j-1)\Delta L}^{j\Delta L} P_{\mathrm{l},j-1} \exp\{[\Gamma g_{\mathrm{l},j}(N_j) - \alpha_\mathrm{int}]z\}\,\mathrm{d}z, \\ = \frac{\exp(\{\Gamma g_{\mathrm{l},j}(N_j) - \alpha_\mathrm{int}]\Delta L\} - 1}{[\Gamma g_{\mathrm{l},j}(N_j) - \alpha_\mathrm{int}]\Delta L} P_{\mathrm{l},j-1}, \quad (5)$$

where ΔL denotes the length of each SOA section, $P_{\mathrm{m},j+1}$ and $P_{\mathrm{l},j-1}$ are the modulation power output from the $(j+1)$th section and mode-locked power output from the $(j-1)$th section, respectively. $g_{\mathrm{m},j}$ and $g_{\mathrm{l},j}$ represent the asymmetric gain of the modulation and mode-locked signal, respectively, and are calculated by

$$g_{\mathrm{m},j} = \frac{a_1(N_j - N_0) - a_2(\lambda_\mathrm{m} - \lambda_N)^2 + a_3(\lambda_\mathrm{m} - \lambda_N)^3}{1 + \varepsilon(P_{\mathrm{m},j} + P_{\mathrm{l},j})}, \tag{6}$$

$$g_{\mathrm{l},j} = \frac{a_1(N_j - N_0) - a_2(\lambda_\mathrm{l} - \lambda_N)^2 + a_3(\lambda_\mathrm{l} - \lambda_N)^3}{1 + \varepsilon(P_{\mathrm{l},j} + P_{\mathrm{m},j})}, \tag{7}$$

where a_1 is the differential gain coefficient, λ_m and λ_l are the central wavelength of the modulation and mode-locked signal, respectively, a_2 and a_3 are empirically determined constants that characterize the width and asymmetry of the gain profile, respectively, ε is the gain compression factor which is phenomenologically introduced to describe the effects of the carrier heating and spectral hole burning, N_0 is the transparency carrier density, $\lambda_N = \lambda_0 - a_4\ (N_j - N_0)$ represents the corresponding peak gain wavelength with λ_0 being the peak gain wavelength at transparency and a_4 denoting the empirical constant that shows the shift of the gain peak.

Based on Eqs. (1)–(7) and using the fourth–fifth-order Runge–Kutta method, for a given input pulse passing through the modulation SOA, the temporal shape of output pulse can be simulated numerically. The procedure of the pulse transmission in the gain SOA can also be simulated with the similar method.

3. Results and discussion

The modulated optical signal output from the gain-switch DFBLD is assumed to be sinusoidal-wave with modulation frequency $f_\mathrm{m} = 2.5\,\mathrm{GHz}$. In this paper, we have assumed that the condition of the harmonic mode locking is satisfied, and the other parameters used in the calculation are: $\Gamma = 0.3$, $L = 5 \times 10^{-4}\,\mathrm{m}$, $\varepsilon = 0.2\,\mathrm{W}^{-1}$, $N_0 = 1.5 \times 10^{24}\,\mathrm{m}^{-3}$, $\lambda_0 = 1605\,\mathrm{nm}$, $\lambda_\mathrm{s} = 1550\,\mathrm{nm}$, $\lambda_\mathrm{m} = 1555\,\mathrm{nm}$, $A = 2.5 \times 10^8\,\mathrm{s}^{-1}$, $B = 1 \times 10^{-17}\,\mathrm{m}^3\mathrm{s}^{-1}$, $C = 9.4 \times 10^{-41}\,\mathrm{m}^6\mathrm{s}^{-1}$, $a_1 = 2.5 \times 10^{-20}\,\mathrm{m}^2$, $a_2 = 7.4 \times 10^{19}\,\mathrm{m}^{-3}$, $a_3 = 3.155 \times 10^{25}\,\mathrm{m}^{-4}$, $a_4 = 3 \times 10^{-32}\,\mathrm{m}^4$, $\alpha_\mathrm{int} = 2 \times 10^3\,\mathrm{m}^{-1}$, $A_\mathrm{cross} = 4 \times 10^{-11}\,\mathrm{m}^2$. Considering that the mode-locked signal pulse is generated from the spontaneous emission in the SOA, the initiated signal is assumed to be of very low power and independent on the time. At first, the initiated signal is modulated based on the cross-gain modulation when it passes through the modulation SOA and is amplified synchronously, then is gain-compensated by the gain SOA, after being attenuated by the OC, finally injects into the modulation SOA. Repeating continuously above process in the calculations, once the self-reproduction is satisfied, the stable mode-locked pulse can be specified.

Fig. 2 shows the pulse evolution for the bias currents of the modulation SOA and the gain SOA are 147 and 70 mA, respectively. From this diagram, it can be seen that, after several thousands of roundtrips, the pulse shape can satisfy self-reproduction. Under this circumstance, we can think that the stable harmonic mode-locked has been realized. The temporal distributing of gain (dashed curve) in the modulation SOA, optical signal (dot curve) output from the sinusoidal-wave-modulation DFBLD and the mode-locked pulse shape (solid curve) are shown in Fig. 3. In Fig. 3(a), the bias currents of the modulation SOA and the gain SOA are 69 and 109 mA, respectively, whereas in Fig. 3(b), the bias currents of the modulation SOA and the gain SOA are 147 and 70 mA, respectively. From the two diagrams, it can be seen that, the pulse width in Fig. 3(b) is much narrower than that in Fig. 3(a). The reason is that, in the high-current-biased modulation SOA, a backward injection can also induce a stronger gain-depletion (or loss) modulation, and this can be proved by the varying extent of gain in the modulation SOA, which can suppress the temporal shift and the pedestal amplitude of the mode-locked pulse. Moreover, a narrower temporal range of the net gain can be obtained when the bias current of the gain SOA is relatively low.

Normalized wave shape out from the mode-locked SOA fiber laser on the different biased condition of the modulation SOA are shown in Fig. 4. The bias current of the gain SOA is 70 mA, and the bias current of the modulation SOA is 174 mA (curve a), 175 mA (curve b), 180 mA (curve c), 185 mA (curve d), 190 mA (curve e), 195 mA (curve f) and 200 mA (curve g), respectively. As we can see, when the bias current of the modulation SOA is 174 mA, pulse width is the narrowest, and pulse is with a symmetrical-temporal-shape. With the increase of the bias current of the modulation SOA, pulse width is gradually widened. Moreover, pulse leading edge

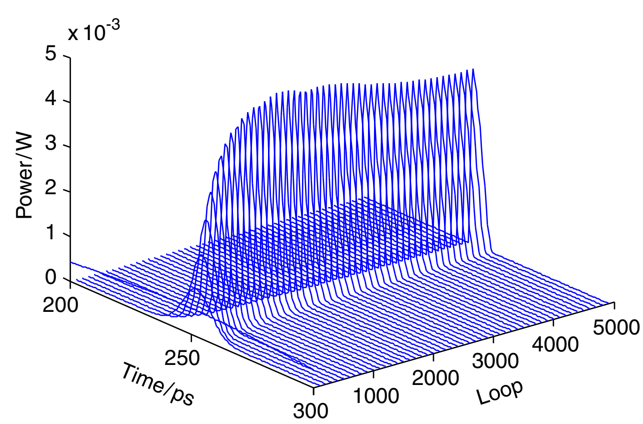

Fig. 2. Temporal shape evolution for the bias currents of the modulation SOA and the gain SOA being 147 and 70 mA, respectively.

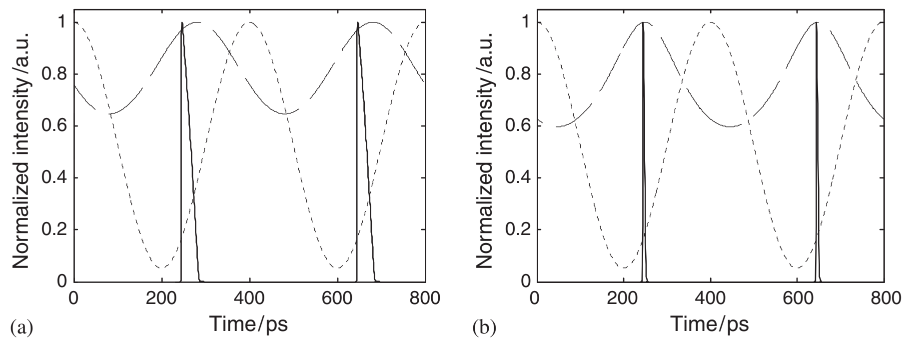

Fig. 3. Temporal distributing of gain (dashed curve) in the modulation SOA, optical signal (dot curve) output from the sinusoidal-wave-modulation DFBLD and the mode-locked pulse shape (solid curve): (a) the bias currents of the modulation SOA and the gain SOA are 69 and 109 mA, respectively and (b) the bias currents of the modulation SOA and the gain SOA are 147 and 70 mA, respectively.

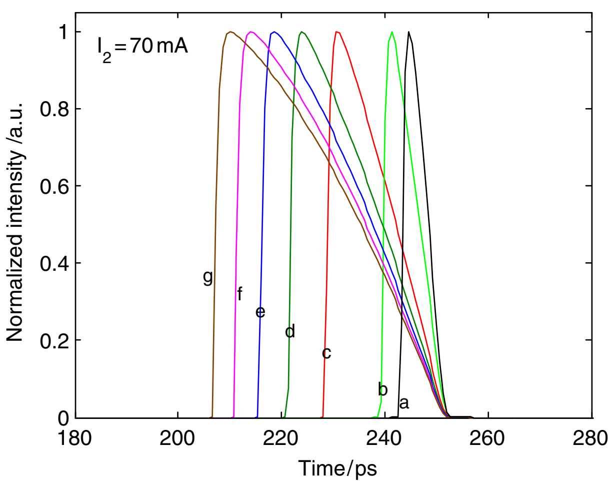

Fig. 4. Normalized wave shape out from the harmonic mode-locked SOA fiber laser on the different biased conditions of the modulation SOA. The bias current of the gain SOA is 70 mA, and the bias current of the modulation SOA is 174 mA (curve a), 175 mA (curve b), 180 mA (curve c), 185 mA (curve d), 190 mA (curve e), 195 mA (curve f) and 200 mA (curve g), respectively.

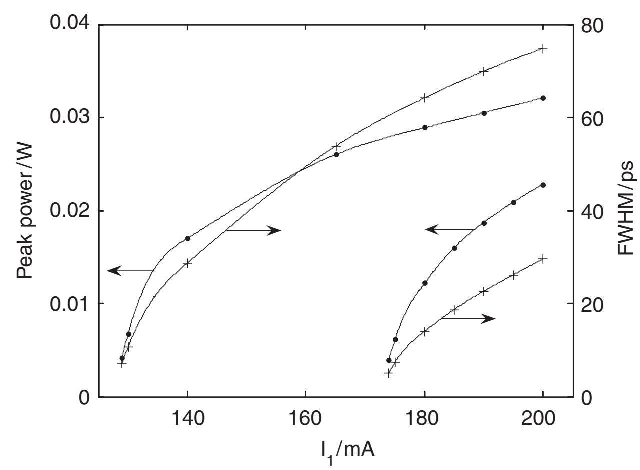

Fig. 5. The peak-power and pulse-width of the mode-locked pulse versus the bias current of the modulation SOA, where the solid curve is for the bias current of the gain SOA $I_2 = 80$ mA and the dot curve is for $I_2 = 70$ mA.

becomes steep and trailing edge becomes slow, which is caused by saturated gain in SOA.

Fig. 5 shows the peak power and pulse width of mode-locked pulse versus the bias current of the modulation SOA, where the solid curve is for the bias current of the gained SOA $I_2 = 80$ mA and the dash–dot curve is for $I_2 = 70$ mA. From this diagram, it can be seen that, with the increase of the bias current of the modulation SOA, the peak power is enhanced and the pulse width is widened, which is easy to understand. Because part of the carriers is depleted by the modulation signal and only the residual carriers are used to amplify the mode-locked pulse, with the increase of the bias current of the modulation SOA, the residual carriers will increase, which results in the increase of the peak power. Meantime, the time range within which the small signal gain is more than cavity loss will be added, which results in the pulse-width widening. On the other hand, if the bias current of the modulation SOA is maintained a constant, different peak powers and pulse widths can be obtained through adjusting the bias current of the gained SOA. Through calculations, it can be concluded that the mode-locked pulse with large peak power and narrow width can be obtained when the bias current of the modulation SOA is DC biased on the enough high current and the current of the gain SOA is DC biased on the relatively low current to realize that the net gain of small signal is larger than zero.

It should be pointed out that, with the increase of the modulation frequency, the peak power of mode-locked pulse will decrease because the gains of the SOAs cannot be fully recovered; moreover, the width of mode-locked pulse will also decrease because of the decrease in net gain time range.

4. Conclusions

It has been numerically proved that a narrower optical pulse train with a more symmetrical-temporal shape can be obtained, when the modulation SOA is DC biased on the high current, whereas the gain SOA is DC biased on the low current functions as a gain compensator in the harmonic mode-locked SOA fiber ring lasers, and the cause has been interpreted. On the new condition, the characters of the harmonic mode-locked pulse on the different bias current of the modulation SOA have been investigated.

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