A novel mode-locked ring laser based on polarization saturation in a semiconductor optical amplifier

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Recently, in our group 800 fs optical pulses were generated in a mode-locked ring laser operated by polarization saturation in a semiconductor optical amplifier (SOA). We investigate numerically the generation of sub-picosecond optical pulses in such a configuration, consisting of a SOA and a linear polarizer placed in a ring. Polarization saturation in the SOA takes the role of a saturable absorber in the passive mode-locking mechanism. Our results are well in agreement with experiment.

1. Introduction

Nonlinear polarization rotation, either induced by a pump signal [1, 2] or the signal itself [3, 4, 5], has been demonstrated to be useful in all-optical signal processing, for example, wavelength conversion, optical logic gates, etc. The possibility of mode-locking based on nonlinear polarization rotation in quantum well SOA was pointed out in [3] and experimentally confirmed [6]. In [3], continuous pulse narrowing was numerically observed and it was ascribed to dispersion effects or ultra-fast dynamics in SOA to stop the narrowing process, but those effects were not taken into account. In our paper, using a consistent model with ultra-fast gain dynamics [7], we will investigate how an initially broad pulse can be shortened using nonlinear polarization rotation in the SOA. Just as [3] anticipated, the final pulse width is found to be limited by the ultra-fast gain dynamics in the SOA, especially the carrier-phonon relaxation time.

2. Principle and Model

The system setup is given in Fig.1. When the input optical intensity (point A in Fig.1) is sufficiently low, the SOA operates in the linear regime. The two orthogonal polarization components in the amplifier (transverse electrical, TE and transverse magnetic, TM), which have the same amplitudes since the polarization at point A is 45 degrees with respect to the TE and TM direction of the SOA, collect different phases and gains. This causes some modified polarization state of the output, which is polarization-independent.

Now suppose the input optical intensity becomes high enough to saturate the amplifier. Then, TE and TM modes collect different phases and amplitudes, which are now intensity-*dependent*. This implies that different parts of the output pulse assume different polarizations and this property makes it possible to cut away the pulse part that suffers the same polarization as in the low intensity input case. This provides the basic mechanism for our mode-locking system.

The nonlinear optical pulse propagation in the SOA is simulated using the model developed in [6]. By representing the vectorial electrical field by the Jones vector, the function of the polarization controller (PC) and polarizer are modeled as matrices that act on the Jones vector. The unitary matrix U, representing PC, can be written as

$$\mathrm{U} = \frac{1}{\sqrt{2\left(\left(\tau_0^{TE}\right)^2 + \left(\tau_0^{TM}\right)^2\right)}} \begin{bmatrix} (\tau_0^{TE} + \tau_0^{TM}) e^{-i\phi_0^{TE}} & (\tau_0^{TM} - \tau_0^{TE}) e^{-i\phi_0^{TM}} \\ (\tau_0^{TM} - \tau_0^{TE}) e^{-i\phi_0^{TE}} & -(\tau_0^{TE} + \tau_0^{TM}) e^{-i\phi_0^{TM}} \end{bmatrix}, \qquad (1)$$

where τ_0^{TE} and τ_0^{TM} are the single-pass transmission and ϕ_0^{TE}, ϕ_0^{TM} the phase shifts in the low intensity input case, which are calculated from simulations. Then U is applied in the high intensity input case to obtain Jones vector before the SOA in the next roundtrip as:

$$\frac{1}{2}\begin{bmatrix}1 & 1\\ 1 & 1\end{bmatrix} \mathrm{U} \begin{bmatrix}\gamma^{TE}\\ \gamma^{TM}\end{bmatrix}, \tag{2}$$

where (γ^{TE}, γ^{TM}) is the Jones vector that represents the field at B. The field, represented by (2), will enter the SOA again.

A Lorentzian spectral filter with a transfer function $f(\omega)=D/[D-i(\omega-\omega_0)]$ is implemented in the simulations to mimic the dispersion effects, which is a limiting factor in experiments (2D is the 3-dB bandwidth of the filter).

3. Numerical results

The SOA has a strained bulk active region of 250 μm and active volume of 50 μm^3 [6]. All other parameters are (TPA stands for two photon absorption): Confinement factor TE/TM/TPA 0.18/0.15/0.5, linewidth enhancement factor TE/TM/TPA 4/4/-1, free carrier absorption coefficients in conduction/valence band 3×10^{-9}/0 μm^2, carrier lifetime 300 ps, gain coefficient TE/TM $1.4\times10^{-5} \mu m^3$/ps,group velocity 100 ps/μm, waveguide loss 0.00175 μm^{-1}, the photon energy is 0.8 eV, carrier-carrier scattering time in conduction/valence band 0.1/0.05 ps and carrier-phonon relaxation time 0.7/0.25 ps, TPA coefficient $2\times10^{-9} \mu m^2$, optical transition state density 3.6×10^5 μm^{-3}. The calculations are performed for 160 mA injection current except stated otherwise. In the calculations, the small signal gain for TE/TM components are 16.75 /14.8 dB.

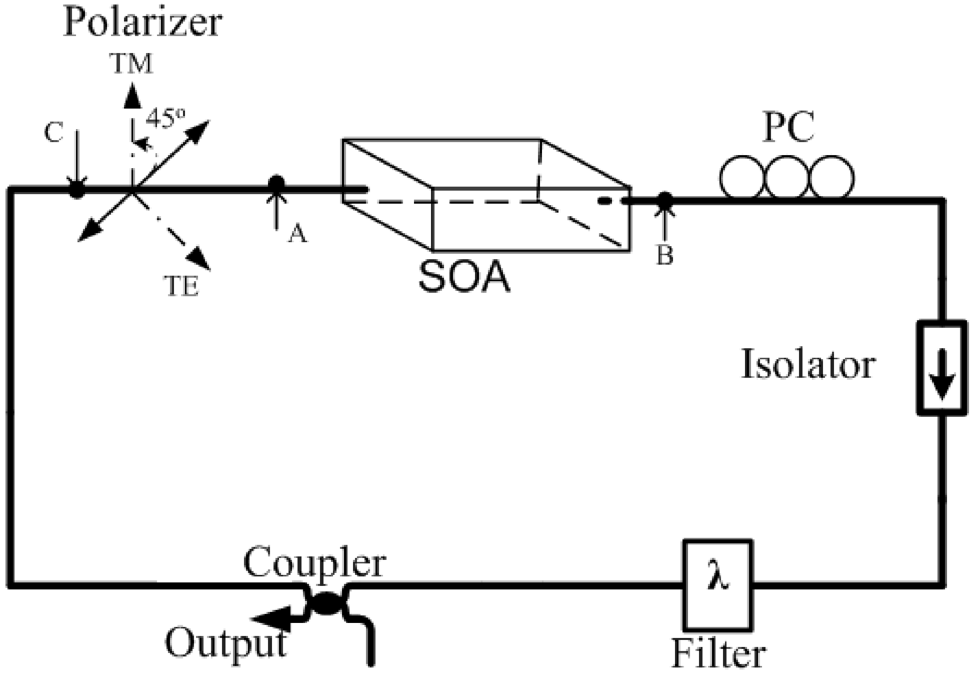

Figure 1: System setup of the SOA-based fiber ring laser, where SOA is a semiconductor optical amplifier, PC is a polarization controller and the linear polarizer has its transmitted polarization under 45 degrees with respect to TE and TM polarization directions of the SOA.

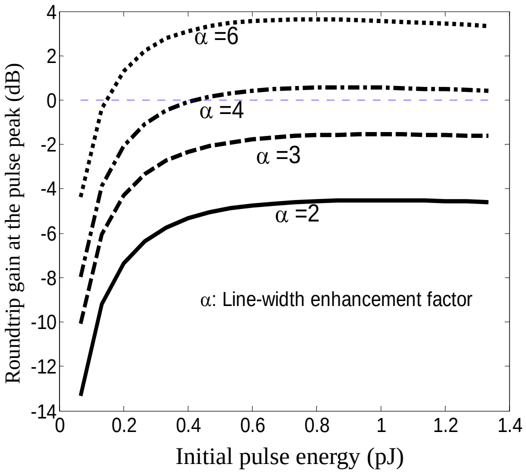

Figure 2: The roundtrip gain at the pulse peak vs. the initial pulse energy for different line-width enhancement factor in the first roundtrip. (Injection current is 160mA)

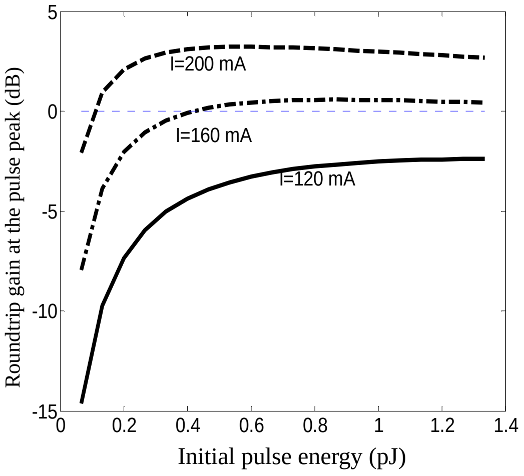

Figure 3: The roundtrip gain at the pulse peak vs. the initial pulse energy for different injection current in the first roundtrip. (Line width enhancement factor is 4)

The roundtrip gain (in dB), which is taken as the ratio between the optical intensity at point A in Fig.1 in the current roundtrip and the previous roundtrip , should be larger than zero for the pulse to build up. In Fig. 2, the roundtrip gain at the pulse peak in the first roundtrip is shown as a function of the input pulse energy for different α, when the injection current is 160 mA. For a given linewidth enhancement factor a, the roundtrip gain can be increased by pumping larger current into the active region, as shown in Fig. 3, where α is 4. However, for very small α it may become impossible to obtain net roundtrip gain because of gain saturation at higher currents.

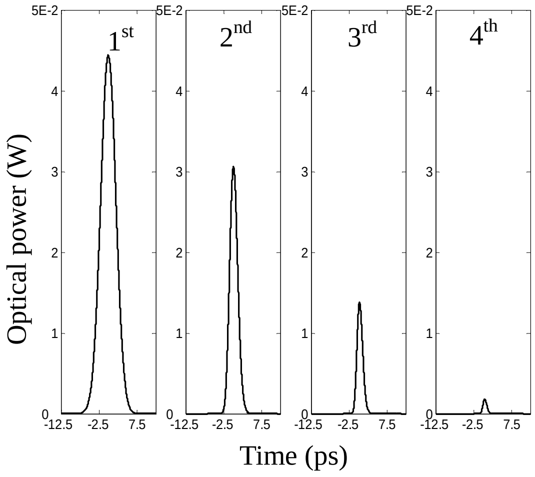

Figure 4: The input pulse has insufficient energy for a net positive roundtrip gain. Therefore, the pulse is attenuated after each roundtrip. Note the narrowing take place. The initial Gaussian pulse has a width of 2ps (RMS), is unchirped and has energy of 0.22 pJ. After a few roundtrips, the pulse has disappeared. The injection current is 160 mA and α is 4.

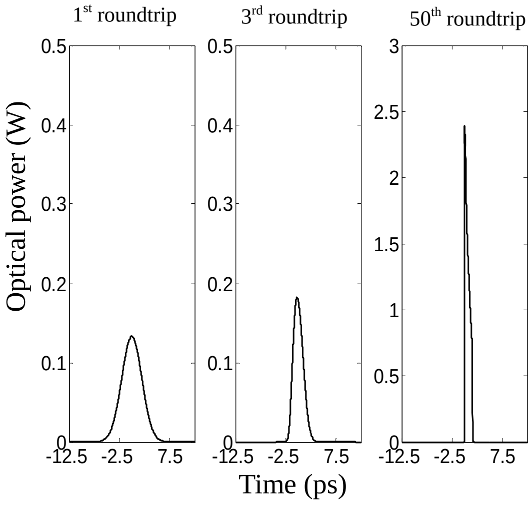

Figure 5: Numerical simulation of the pulse built-up. Initially the pulse has duration of 2 ps and its energy was 0.66 pJ. After 2 roundtrips the pulse duration has decreased to 815fs and the pulse energy has decreased to 0.45 pJ. After 25 roundtrips the pulse has been shorted further to the ultimate width of 537 fs and energy 2.33 pJ. The filter bandwidth was taken 3.2 THz (FWHM). Pulse width is RMS width. Other parameters are as in Fig.4.

Input pulses with insufficient intensity cannot induce large enough phase shifts between TE and TM components for the pulse to acquire positive roundtrip gain. This is shown in Fig.4, where a 2ps (RMS), 0.22 pJ Gaussian input pulse is seen to decrease after each roundtrip. When the input pulse peak intensity is increased, beyond a critical value, the pulse is amplified and narrowed in every loop and after several tens of roundtrips the pulse has evolved into a stable output. This is shown in Fig.5 for an unchirped Gaussian shaped input pulse of 2 ps (RMS) duration and 0.66 pJ energy and a filter of 3.2 THz (FWHM) was used. One observes in Fig. 5 that after about 25 roundtrips the stable state is achieved, which is characterized by 537 fs (RMS) duration output pulses with energy of2.33 pJ.

We also performed simulations in which the cavity length is assumed to be so short that the SOA can not fully recover during one roundtrip. We found that a maximum repetition rate existed where above the laser switched off. This happens because at high repetition rate the gain depletion after one pulse is such that the next pulse has negative net roundtrip gain. Indeed, the carrier lifetime and current play crucial role in this. The pulse repetition rate is limited to 5 GHz when the carrier lifetime is assumed to be 300 ps. The pulse repetition rate is increased to 20 GHz when the carrier lifetime is assumed to be 200 ps while decreased to about 2.5 GHz when the carrier lifetime is assumed to be 500 ps. No optimization of the system has been done to increase the bit rate yet.

4. Conclusion

In conclusion, the pulse narrowing process in a passive mode-locking system based on nonlinear polarization rotation in a SOA was modeled and simulated. If dispersion is compensated for, the ultimately achievable pulse width(~500 fs) is restricted by ultrafast gain dynamics in the SOA.

Acknowledgments

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