Numerical modeling of sub-picosecond counter-propagating pulses in semiconductor optical amplifiers

Mohammad Razaghi[1], Vahid Ahmadi[2], Michael J. Connelly[3] and Kazhal Alsadat Madanifar[4]

1. Dept. of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, Iran
2. Dept. of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran
3. Dept. of Electronic and Computer Engineering, University of Limerick, Limerick, Ireland
4. Dept. of Electrical Engineering, K. N. T. University of Technology, Tehran, Iran

Email: mrazaghi@uok.ac.ir

Abstract— **The use of counter-propagating sub-picosecond pulses to modify the temporal shape and spectrum of a probe pulse in an SOA is investigated using a modified nonlinear Schrödinger equation (MNLSE), which includes all of the dynamical processes relevant to the sub-picosecond range. The MNLSE is solved using a novel numerical method based on trapezoidal integration and central difference techniques. It is shown that by using the counter propagation scheme besides amplification, both time and spectral profile of the propagated pulse are compressed. Furthermore, the output pulse distortion caused by nonlinear phenomena in SOA is improved.**

I. Introduction

Suitable models of ultra-short pulse propagation in SOAs are of fundamental importance for understanding carrier dynamics and nonlinear effects can be utilized for implementing all-optical signal processing functions.

In this paper, we use an improved finite difference beam propagation method (IFDBPM) [1], to model the temporal and spectral properties of counter propagating picosecond optical pulses, which are amplified by an SOA. The analysis is based on a MNLSE considering group velocity dispersion (GVD), inter-band gain and refractive index dynamics, two-photon absorption (TPA), ultra-fast nonlinear refraction (UNR), carrier heating (CH), spectral-hole burning (SHB), their dispersions and gain dispersion in an SOA. It is shown that by using this scheme, output probe pulse temporal and spectral peak shift due to nonlinearities can be compensated, while the output pulse is amplified sufficiently. Furthermore, the probe time-bandwidth product (TBP) is improved using suitable counter-propagation pump pulse.

II. Modified Nonlinear Schrödinger Equation

The MNLSE which describes the propagation of forward and backward optical field with complex amplitude $A^{\pm}(z,t)$ is given by [1-3]:

$$\left[\pm\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}\right]A^{\pm}(z,t)=\left\{\frac{i}{2}\beta_2\frac{\partial^2}{\partial t^2}-\left(\frac{\gamma_{2p}}{2}+ib_2\right)I(z,t)\right.$$

$$-\frac{\gamma}{2}+\frac{1}{2}g_N(t)\left[\frac{1}{f_T(t)}+i\alpha_N\right]+\ \frac{1}{2}\Delta g_T(t)\left[1+i\alpha_T\right]$$

$$\left.-i\frac{1}{2}\frac{\partial g(t,\omega)}{\partial\omega}\bigg|_{\omega_0}\frac{\partial}{\partial t}-\frac{1}{4}\frac{\partial^2 g(t,\omega)}{\partial\omega^2}\bigg|_{\omega_0}\frac{\partial^2}{\partial t^2}\right\}A^{\pm}(z,t)\quad(1)$$

In (1), β_2 is the GVD coefficient and v_g is the group velocity at transparency, $I(z,t)=|A^{+}(z,t)|^2+|A^{-}(z,t)|^2$. γ is the linear loss, γ_{2p} is the TPA coefficient, b_2 is the instantaneous self-phase modulation term due to the UNR. $g_N(t)$ is the saturated gain due to carrier depletion, $f_T(t)$ is the SHB function, $\Delta g_T(t)$ is the resulting gain change due to the CH and TPA and α_N and α_T are the linewidth enhancement factor associated with the gain change due to carrier depletion and CH.

III. Numerical Technique

For solving (1) we used a central differentiation and trapezoidal integration techniques over a small step size Δ in new frame which is rotated to $(z,T=v_g t)$ coordinates. Δ is defined as L/M where L is the SOA length and M is number of sections. To find the state of the system at each point, the state of adjacent points must be known (Fig. 1). Using this method, a set of MNLSEs in the counter propagation regime can be solved with high precision in just a few seconds [1].

IV. Results

The applicability and precision of the model have been validated through comparison to experimental results [1]. In the following results the material parameters are used from [3]. The incident complex amplitude can be written as:

$$A^{\pm}(0,t)=\left(E_{in}/(2t_0)\right)^{1/2}\times\mathrm{sech}\left(-(t/t_0)\right)\times\exp\left(-iC/2\times(t/t_0)^2\right)\quad(2)$$

where E_{in} is the input pulse energy, t_0 is related to input pulse FWHM by $T_{FWHM}\approx1.763t_0$ and C is the chirp parameter. The temporal and spectral shapes of short optical pulses as they propagate through an SOA can change significantly. A suitable counter-propagating pump pulse can lead to an improved output probe shape and spectrum. As shown in Fig. 2 the output probe peak position can be shifted to its initial position in presence of pump pulse. As can be observed the output probe pulse is also compressed by 30% from its initial value. In Fig. 3 the effect of pump pulse on probe pulse spectrum is shown. Based on the results in the absence of pump pulse output probe peak is blue shifted. Counter propagating pump pulse can be used to compensate this shift for both positive and

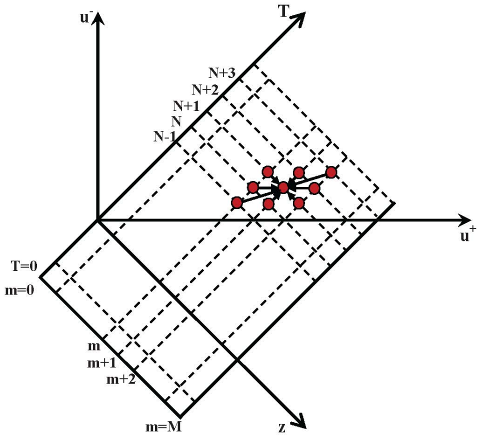

Fig. 1. Integration domain in the new coordinates u^{+} and u^{-}.

negative input probe chirp parameters. Besides the output probe spectrum is compressed to half of its input spectral width in this regime. Therefore the TBP of output probe pulse is decreased significantly in this case as both time and spectral profile of output probe are compressed. The effects of unchirped pump pulse energy on probe pulse for different chirp values and detuning frequencies are also investigated in Fig. 4. Based on the results in some cases the probe peak shift in absence of pump pulse becomes as large as 90 fs. This value is comparable with the pulse output pulsewidth which in this case is 350 fs. Injection of a pump pulse that is counter-propagating to the probe pulse can be used to reduce the probe pulse distortion. Moreover, the propagated pulse in this regime has an acceptable amplification factor as shown in Fig. 5. The effect of time delay between input pump and probe pulses on output probe TBP is illustrated in Fig. 6. It shows that TBP improves as the input pump pulse energy is increased.

References

[1] M. Razaghi, V. Ahmadi, and M. J. Connelly, "Comprehensive Finite-Difference Time Dependent Beam Propagation Model of Counter-Propagating Picosecond Pulses in a Semiconductor Optical Amplifier," J. of Lightwave Technol., accepted (2009).

[2] H. Aghajanpour, V. Ahmadi, M. Razaghi, "Ultra-short optical pulse shaping using semiconductor optical amplifier," *J. of Optics & Laser Technology,* Vol. 41, pp. 654–658. 2009.

[3] M. Y. Hong *et al.* "Femtosecond self- and cross-phase modulation in semiconductor laser amplifiers," *IEEE J. Selected topics in Quantum Electron.*, vol. 2, no. 3, pp. 523-539, Sep.1996.

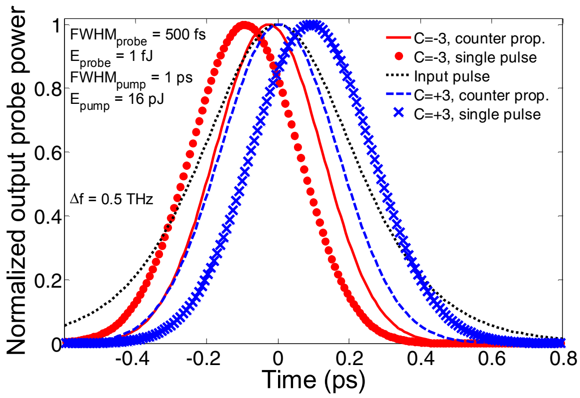

Fig. 2. Normalized output probe shape for different energies of counter-propagating pump pulse and chirp parameters.

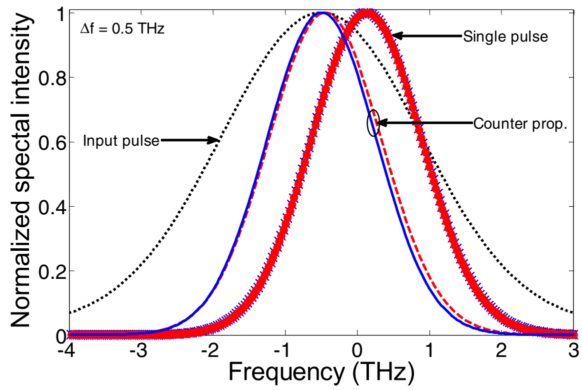

Fig. 3. Normalized output probe spectrum for different energies of counter-propagating pump pulse and chirp parameters.

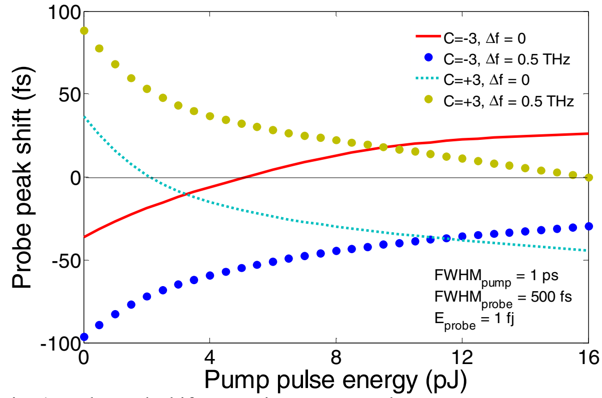

Fig. 4. Probe peak shift versus input pump pulse power.

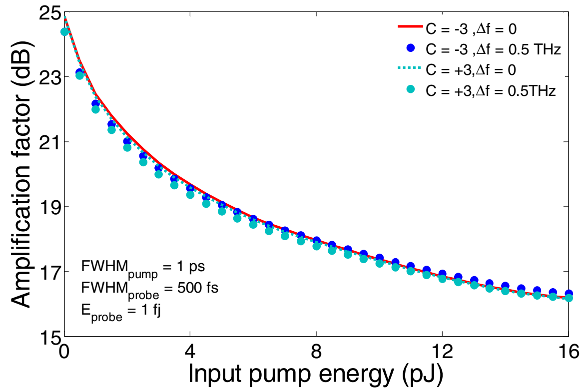

Fig. 5. Amplification factor versus input pump pulse power.

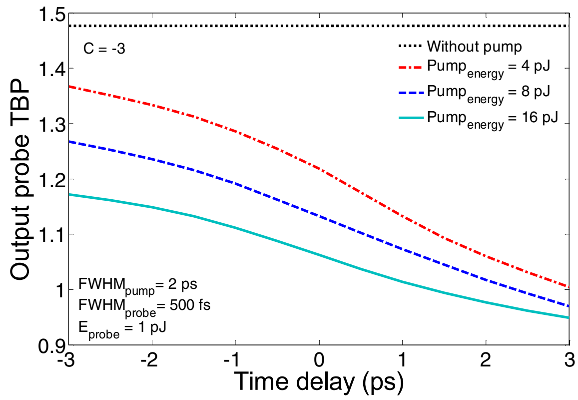

Fig. 6. Output probe pulsewidth as a function of time delay between pump and probe pulses for several input pump pulse energies.