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Nonlinear Process between Co-propagating Signal and Control Pulses in Semiconductor Optical Amplifiers

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Abstract

A nonlinear process between co-propagating signal and control pulses has been proposed and demonstrated numerically, based on semiconductor optical amplifiers (SOA). Results show that a Gaussian signal pulse with picosecond duration can be simultaneously amplified and compressed in a SOA by utilizing a co-propagating high-intensity control pulse. To obtain high quality signal pulse with high peak power level and short pulse width, the center carrier wavelengths of two pulses should locate in the gain region of the SOA. The initial delay time between both pulses should be tuned suitably before entering the SOA.

Key Words: Nonlinear optics; pulse propagation and shaping; semiconductor optical amplifiers.

1. Introduction

Semiconductor optical amplifiers (SOA) with large gain bandwidth and high nonlinear effects are easily integrated with other semiconductor devices, whose wavelength of operation can span the entire range of communications wavelengths with low loss. The SOA thus plays an important role in the modern optics communications systems. Because of long gain recovery time for SOA, the amplified signal pulse becomes asymmetric, with the leading edge of pulse becoming steeper than the trailing edge, and extension of the pulse width [1–2]. Such is the motivation to compress and shape the Gaussian signal pulse amplified by the SOA. Only, few effective methods have been explored and applied. In this work, we explore a feasible pulse-shaping method to absorb the energy of the trailing edge of the amplified signal. We propose and demonstrate a Gaussian signal pulse with picosecond duration can be simultaneously amplified and compressed using a co-propagating 2^{nd} super-Gaussian control pulse with high peak power, when the initial delay time between both of pulses is chosen correctly before entering the SOA. The project proposed has some advantages: operation is simple; the signal pulse amplified has the properties of high peak power, short pulse width and symmetric waveform, which is significant to increase transmission distance and reduce inter-symbol interference in optics communications.

Remainder of this paper is organized as follows. In section 2, equations describing propagation are presented. In Section 3, we display the simulation results and discussions. Section 4 summarizes the work.

2. Propagation Equations

The SOA has been segmented into a number of smaller sections, whose facet reflectivity is equal to zero. Theoretical analysis is based on the numerical solution of the differential carrier rate equation for each section, and that the propagation equations for the control and signal pulses are modeled as [3–5]

$$\frac{\partial N_j(z,T)}{\partial T} = \frac{I}{qV} - \frac{N_j}{\tau_c} - \sum_w \frac{\Gamma g_{w,j}(N(z,T))}{\hbar\omega_w A_{\text{cross}}} \cdot \frac{\bar{\bar{P}}_{w,j}}{1+\varepsilon \bar{P}_{w,j}} \quad (1)$$

$$\frac{\partial P_w(z,T)}{\partial z} = \Gamma(g_w(N(z,T)) - \alpha_{int})P_w(z,T). \quad (2)$$

Here, j and w correspond to the different amplifier sections and input optics wavelengths, respectively;N_j is the carrier density; $T = t - z/V_g$, where V_g is the group velocity in the SOA, and is measured in a reference frame moving with the pulse; I is the injection current; V is the volume of each SOA; q is the electron charge; $\hbar\omega$ is the photon energy; A_{cross} is the cross-sectional area of the active layer; ε is a nonlinear gain compression factor; $\tau_c$is the spontaneous emission carrier lifetime; and $1/\tau_c = A + BN + CN^2$, A, B and C being nonradiative, bimolecular and Auger recombination constants, respectively; is the confinement factor, α_{int} is internal loss; P_w is the optical power; $\underset{w,j}{\bar{P}}$ is the average power in the section j, which is calculated by [6]

$$\underset{w,j}{\bar{\bar{P}}} = \frac{1}{\Delta L}\int_{(j-1)\Delta L}^{j\Delta L} P_{w,j-1} e^{(\Gamma g_w(N) - \alpha_{in})z} dz = \frac{G_j - 1}{\ln(G_j)} P_{w,j-1}, \quad (3)$$

where $G_j = e^{(\Gamma g_w(N) - \alpha_{in})\Delta L}$;$\Delta L$is the length of each section; and $P_{w,j-1}$is the output power of section $j-1$. In order to model the asymmetric gain, a cubic formula is used [7]:

$$g_w(N) = a_1(N - N_0) - a_2(\lambda - \lambda_N)^2 - a_3(\lambda - \lambda_N)^3, \quad (4)$$

where a_1 is the differential gain,a_2 anda_3 are gain constants,$\lambda_N (= \lambda_0 - a_4(N - N_0))$is the gain peak wavelength, and a_4 is the material gain constant.

The input powers of the 2^{nd} super-Gaussian control pulse and signal pulse can be expressed by

$$P_2 = P_{20} \exp\left[-\left(\frac{T - T_d}{T_0}\right)^4\right] \quad (5)$$

$$P_s = P_{s0} \exp\left[-\left(\frac{T}{T_0}\right)^2\right], \quad (6)$$

where P_{20} and P_{s0} are the input peak powers of the control and signal pulses, respectively. T_0 is the half width of input control at 1/e intensity point. T_d is the initial delay time between the control and signal pulse.

3. Results

Figure 1 and 2 show respectively the normalized signal pulse shapes with and without the control pulse. The adopted parameters in calculations are $P_{20} = 100$ mW; $P_{s0} = 10$ mW; $A_{cross} = 0.3$ μm^2; $V = 150$ μm^3;$I = 150$ mA; $\varepsilon = 0.2$ W^{-1}; $N_0 = 0.9\times10^{24}$ m^{-3}; λ_0=1605 nm; $\alpha_{int} = 20$ cm^{-1}; $\Gamma = 0.3$; $A = 2.5\times10^8$s^{-1};$B = 1.0\times10^{-16}$ m^{3}s^{-1}; $C = 0.94\times10^{-40}$ m^{6}s^{-1}; $a_1 = 2.5\times10^{-20}$ m^2; $a_2 = 7.4\times10^{18}$ m^{-3}; $q = 1.6\times10^{-19}$ C; $a_3 = 3.155\times10^{25}$ m^{-4}, $a_4 = 3\times10^{-32}$ m^4; the two pulse widths are each $T_0 = 10$ ps; SOA length $L = 500$ μm; SOA is divided equally into 100 sections; the center wavelengths of control and signal pulses are $\lambda_2 = 1558$ nm, $\lambda_s = 1550$ nm, respectively. In Figure 1 we can see that the amplified signal pulse has a steeper leading edge than the trailing edge, whose pulse width is extended, and pulse shape has been seriously distorted, without the presence of the control pulse. However, when the control

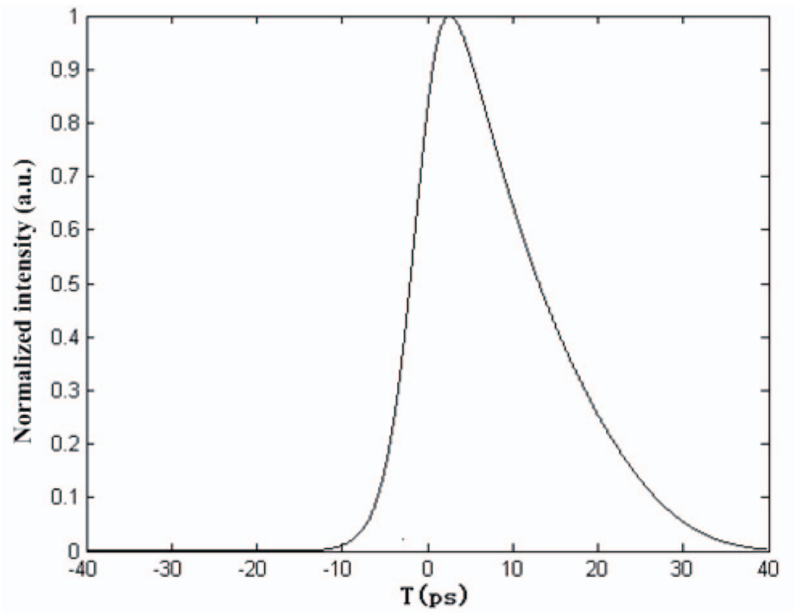

Figure 1. The normalized shape of output signal pulse without control pulse.

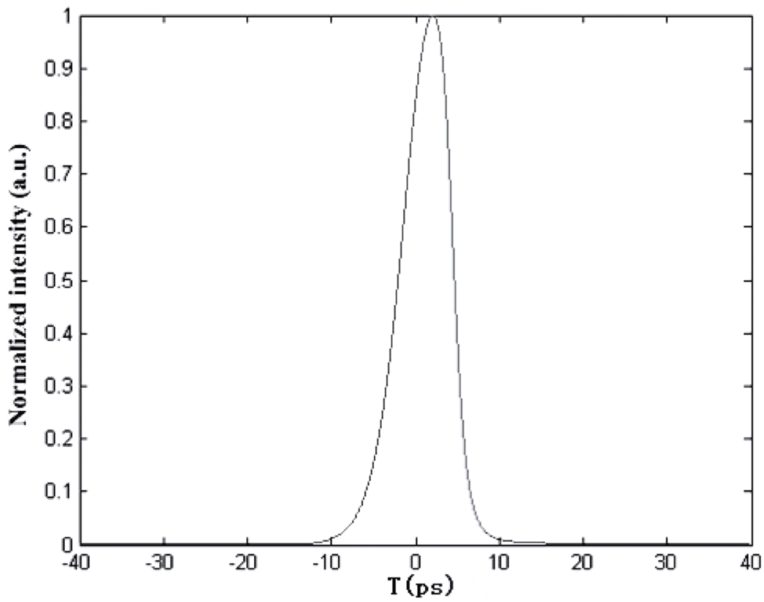

Figure 2. The normalized shape of output signal pulse with control pulse.

pulse is introduced, the amplified signal pulse exhibits a short pulse width and symmetric waveform. From a large number of numerical simulations we have found that the amplified signal pulse has nearly symmetric waveform when the control pulse has the second-order super-Gaussian shape. In the following paragraphs, we will respectively discuss the influences of initial delay T_d, center wavelength of control pulse λ_2, and input peak of the control pulse P_{20} on the signal pulse through the SOA.

3.1. Influence of T_d

Figure 3 shows the normalized outcome pulse for different T_d. The other simulation parameters are identical to that of Figure 2. As can be seen from the figure, the output pulse has narrow pulse width and nearly symmetric waveform for $T_d \leq 0$; this denotes the signal pulse lags the control pulse on entering the SOA. At T_d = -12 ps, the output signal pulse has a small side lobe near the trailing edge. For $T_d \geq 0$, i.e., the control pulse lags the signal pulse on input to the SOA, the output pulse width is gradually extended and its trailing edge is gradually prolonged with increase of T_d. Such behavior can be explained: as both pulses co-propagate through the SOA, with $T_d \leq 0$, the leading edge of the signal pulse is efficiently amplified; yet the energy of the trailing edge is suppressed since the effect of the high intensity co-propagating control pulse causes the SOA to enter saturation, and in turn, the energy of the trailing edge of the amplified signal pulse is effectively absorbed by the SOA. The consequence is simultaneously amplifying and shaping the signal pulse with low power level in SOA—effected by tuning properly the initial delay time T_d. Another noticeable issue is that when T_d arrives at -12ps, a sidelobe occurs near the trailing edge of the output signal pulse due to long carrier recovery time. On the other hand, for $T_d \geq 0$, the trailing edge of signal pulse will also obtain gain, resulting in a long trailing edge and asymmetric waveform. In fact, when positive T_d is sufficiently large, i.e., both of pulses are completely separate in temporal domain, the property of output signal pulse is same as for the case P_{20}=0.

To display changes of pulse width and peak power, Figure 4 plots the full width at half maximum (FWHM) and peak power of output signal pulse as a function of T_d, in which it is clearly shown that the pulse width and peak will gradually increase, and reach a stable level, when T_d varies from -12 ps to 12 ps. Based on Figures 3 and 4, when other parameters are determined, the initial delay time should range from -10 ps to 0 to achieve high quality outcome pulse.

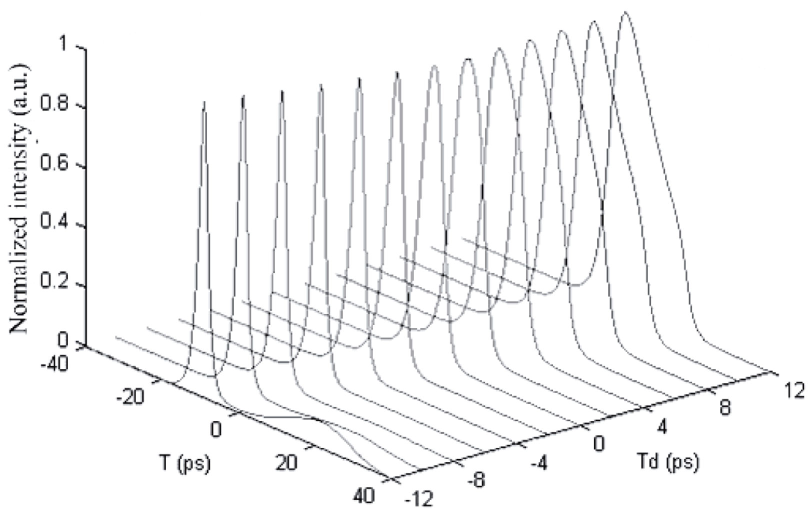

Figure 3. The normalized shapes of output signal pulse for different T_d.

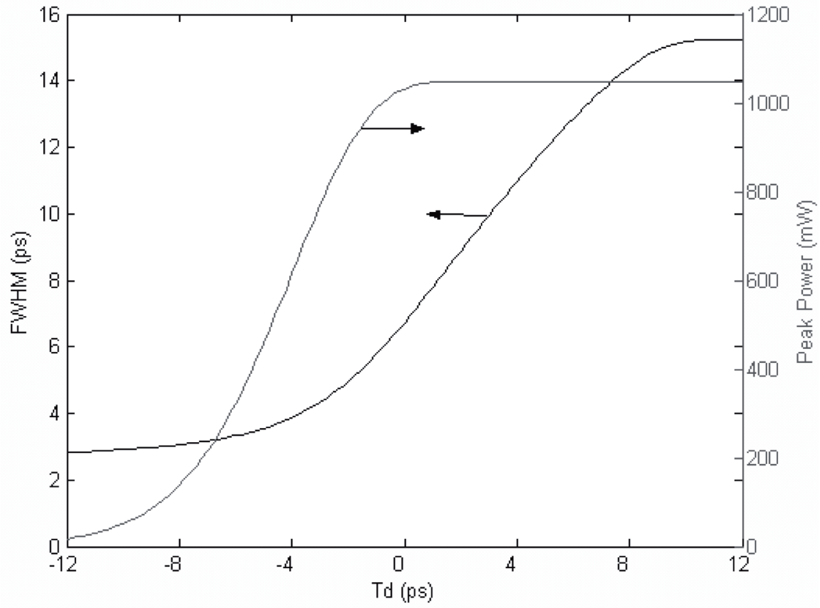

Figure 4. The variation curves of peak power and pulsewidth of output signal pulse versus T_d.

3.2. Influence of λ_2

Figure 5 shows the normalized waveforms of output signal pulse for different λ_2. The parameters adopted are identical to those that give Figure 2. Figure 5 indicates high quality output pulse can be achieved for control pulse wavelength λ_2 near 1550 nm. The physical principle is this: when the control pulse wavelength locates in the gain region (near 1550 nm), the high-intensity control pulse will affect the SOA gain saturation such that the energy of the trailing edge of the signal pulse is absorbed; that is, the long signal trail is effectively suppressed. Hence, the outcome pulse presents a short pulse width and nearly symmetric

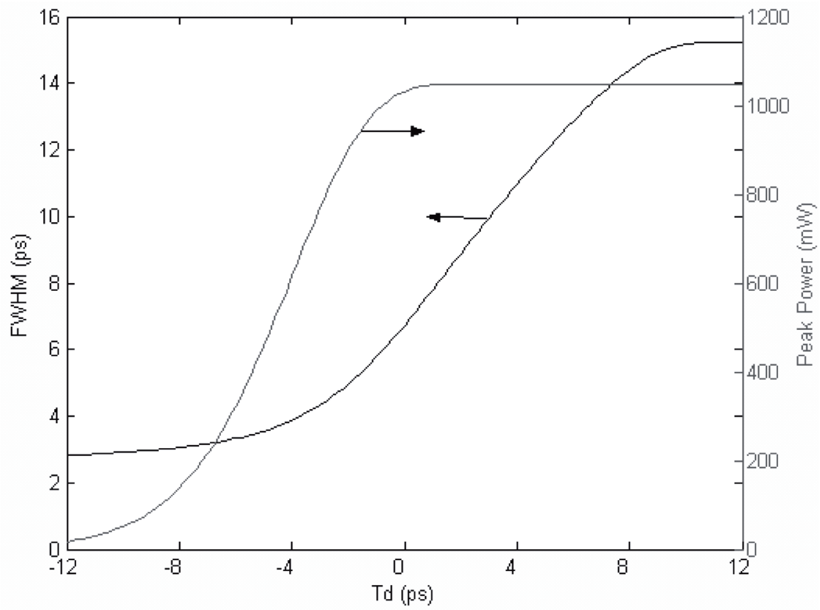

Figure 5. The normalized shapes of output signal pulse for different λ_2.

waveform. If λ_2 is outside the gain region of the SOA, the energy of the control pulse will be absorbed, from which the trailing edge of the signal pulse will obtain more gain, leading the output pulse to exhibit a long trailing and extended pulse width. Figure 6 shows the corresponding pulse width and peak power as a function of various λ_2, in which it is clearly shown that pulse width and peak power will experience process of decrease, and then increase, as λ_2 varies from 1450 nm to 1650 nm. Therefore, based on the phenomena exhibited in Figures 5 and 6, high quality outcome pulse can be generated when λ_2 locates in the gain region of SOA, i.e. near 1550 nm.

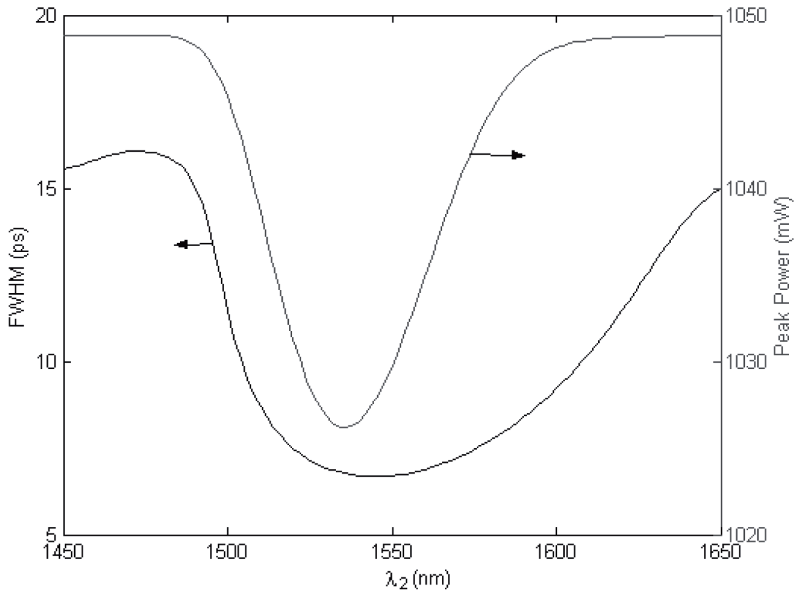

Figure 6. The variation curves of peak power and pulse width of output signal pulse versus λ_2.

3.3. Influence of P_{20}

In this paragraph, we focus on the influence of P_{20} on the outcome pulse, as shown in Figures 7 and 8. Here, we can see that the output pulse has a long trailing edge when P_{20} is low power, and its trailing edge can be suppressed effectively by means of increasing the input control pulse power; other parameters for simula-

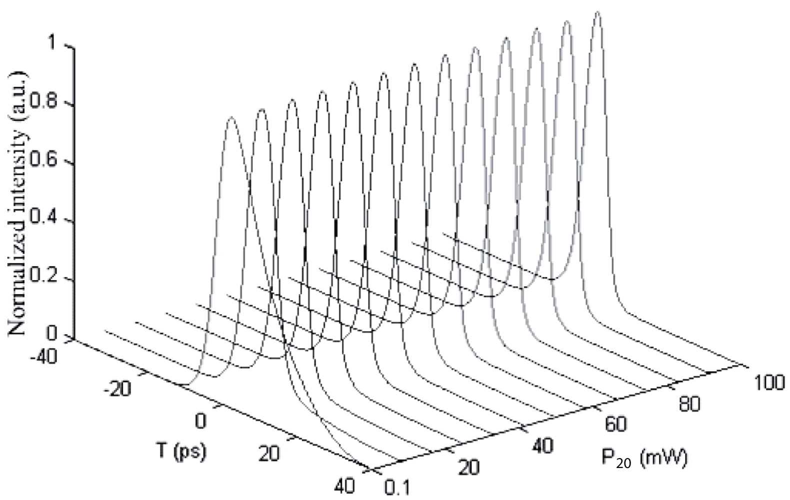

Figure 7. The normalized shapes of output signal pulse for different P_{20}.

tion are same, as in Figure 2. The phenomena arise from the introduction of low power control pulse into the SOA. The SOA can not achieve saturation; so the trailing edge of the signal experiences greater gain and a longer tail on output. The corresponding peak and pulse width are shown in Figure 8. We can see here that the output pulse with high peak level and short pulse width can be achieved for P_{20} between 10 mW and 100 mW.

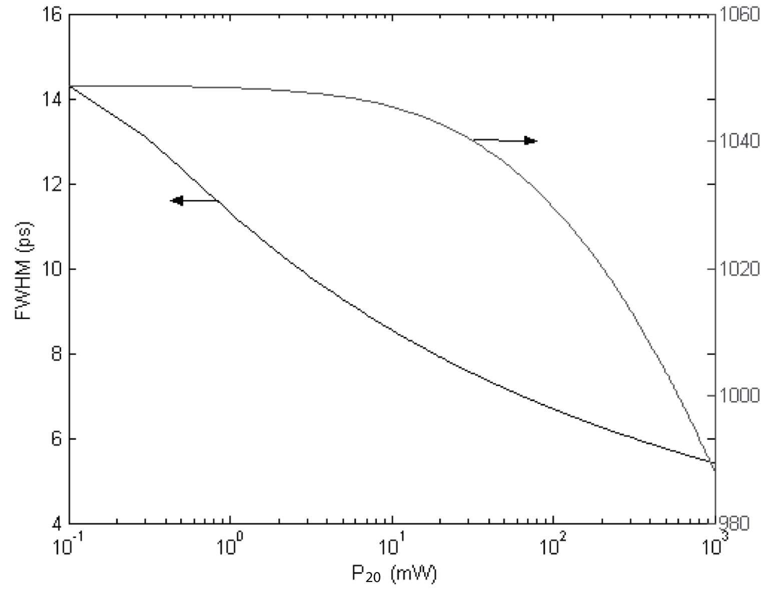

Figure 8. The variation curves of peak power and pulsewidth of output signal pulse versus P_{20}.

4. Conclusions

In this paper we have proposed and demonstrated that a signal pulse with picosecond duration can be amplified and compressed simultaneously by utilizing a co-propagating high-intensity control pulse with 2^{nd} super-Gaussian shape when the initial delay time between both pulses is chosen suitably before entering the SOA. To obtain a high quality outcome pulse with high peak and short pulse width, three conditions must be satisfied: (i) The initial delay time between the control pulse and signal pulse should be $T_d \leq 0$. (ii) The center wavelength of the controlling pulse should locate in the SOA gain region. (iii) The input controlling pulse should have high peak power.

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