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Intraband effects on ultrafast pulse propagation in semiconductor optical amplifier

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Abstract. High bit-rate (>10 Gb/s) signals are composed of very short pulses and propagation of such pulses through a semiconductor optical amplifier (SOA) requires consideration of intraband phenomena. Due to the intraband effects, the propagating pulse sees a fast recovering nonlinear gain which introduces less distortion in the pulse shape and spectrum of the output pulse but introduces a positive chirping at the trailing edge of the pulse.

Keywords. Semiconductor optical amplifier; interband effects; intraband gain dynamics; self-phase modulation.

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1. Introduction

As the data flowing through the communication channels increase at a very fast rate, electronic devices will fail to keep pace because of their limited bandwidth. An alternative solution to this problem is to make all-optical devices, which will not require any conversion to the electronic regime. An optimistic candidate to compete with this fast increasing data rate may be the semiconductor optical amplifier (SOA) whose non-linear effects have been studied for different all-optical device applications such as in-line amplifiers, demultiplexers, wavelength converters and optical switches in optical communication [1]. It shows the potentiality to become an important component of the future all-optical communication network. Our study is focussed on wavelength conversion in SOA using the cross-gain modulation technique based on the nonlinearity induced by gain saturation.

SOAs work well for signal rates within 10 Gb/s, but as the signal rate increases, gain-induced nonlinearities start to affect the output signal. Generally, at lower bit-rates the gain variation of the pulses inside the amplifier is mostly governed by the interband carrier recombination lifetime τ_s, but for higher signal rates when the input signal pulses become very short (pulse width in the order of the intraband relaxation times), then the gain of the amplifier gets modulated because of the intraband effects. The intraband effects are the carrier heating (CH), spectral hole burning (SHB) and two-photon absorption (TPA) that mostly affects the gain of the amplifier. Thus, introduction of the intraband effects is crucial for ultrashort signal pulses when predicting the wavelength conversion or other SOA-based device dynamical characteristics.

A detailed experimental investigation was carried out by Hall *et al* [2] on the propagation of subpicosecond pulses in InGaAsP diode lasers. The propagation of short Gaussian and super-Gaussian pulses in laser amplifiers were solved analytically neglecting the intraband effects by Agrawal and Olsson [3]. Uskov *et al* [4] have presented theoretical results, using density matrix formulation, on wave-mixing in travelling wave semiconductor laser amplifiers in the presence of intraband effects like carrier-density pulsation (CDP), CH, and SHB. Mecozzi and Mørk [5,6] extended the model of [3] by incorporating the effects of CH and SHB to analyse saturation effects and non-degenerate four-wave mixing of very short pulses. Utilizing the intraband nonlinear gain, non-inverted wavelength conversion at high signal bit rates has been achieved using a variable bandwidth optical band-pass filter [7,8].

Here we study the effect of the intraband phenomena on ultrashort pulses propagating through the SOA. We show that the fast intraband phenomena reduce the distortion of the output pulse shape and spectrum. For a pump current of 700 mA, corresponding to an unsaturated gain of 30 dB, we find that the chirping is reduced by about 60% but a positive chirping is also observed which are absent when intraband effects are not taken into consideration.

2. Intraband effects on ultrafast pulse propagation in SOA

When ultrashort pulses propagate through an SOA, the pulse shape and the spectra of the output pulse get modulated. As shown by Agrawal and Olsson [3], for such pulses the pulse peak shifts towards the leading edge giving a deformation to the Gaussian pulse. But pulses with pulse width on the order of τ_{s}, undergoes both pulse and spectrum distortions. Here we present a model to predict the effect of intraband dynamics on ultrashort pulses, utilized for wavelength conversion and compare it with the case when the intraband effects are neglected taking the same pulse width for both the cases. For simulation we consult the model of Mecozzi and Mørk [6] and Agrawal and Olsson [3]. The SOA considered for the simulation is a polarization-independent, bulk heterostructure InGaAsP/InP SOA operating in the C communication band. Then considering propagation of short Gaussian pulses through the SOA we study the gain, spectra and chirping properties of the output pulse. The rate equations are in terms of the integrated gains $h_j(t)$ for the interband carrier recombination ($j = N$) and intraband effects like spectral hole burning ($j = \mathrm{SHB}$) and carrier heating ($j = \mathrm{CH}$), and t is the reduced time ($t = t' - z/v_{\mathrm{g}}$). The reduced time is in the reference frame fixed on the pulse. In this frame, we only need to solve the rate equations of the integrated gain without going into the detailed change occurring within the SOA, though physically the output pulse is always delayed with respect to the input pulse by the time taken to traverse the length of the SOA. The rate equations for the integrated gains $h_j(t)$ are

$$\frac{\mathrm{d}h_{\mathrm{N}}}{\mathrm{d}t} = -\frac{h_{\mathrm{N}}}{\tau_{\mathrm{s}}} - \frac{1}{S_{\mathrm{s}}\tau_{\mathrm{s}}}[G(t,z)-1]S(t,0) + \frac{g_0(z)}{\tau_{\mathrm{s}}}, \tag{1a}$$

$$\frac{\mathrm{d}h_{\mathrm{SHB}}}{\mathrm{d}t} = -\frac{h_{\mathrm{SHB}}}{\tau_{\mathrm{SHB}}} - \frac{\varepsilon_{\mathrm{SHB}}}{\tau_{\mathrm{SHB}}}[G(t,z)-1]S(t,0) - \frac{\mathrm{d}h_{\mathrm{CH}}}{\mathrm{d}t} - \frac{\mathrm{d}h_{\mathrm{N}}}{\mathrm{d}t}, \tag{1b}$$

$$\frac{\mathrm{d}h_{\mathrm{CH}}}{\mathrm{d}t} = -\frac{h_{\mathrm{CH}}}{\tau_{\mathrm{CH}}} - \frac{\varepsilon_{\mathrm{CH}}}{\tau_{\mathrm{CH}}}[G(t,z)-1]S(t,0), \tag{1c}$$

where S_{s} is the satuation photon density of the amplifier and g_0 is the material gain of the amplifier before the pulse starts propagatng through it. $S(t,z)$ gives the photon density of the probe or pump signal at a position z along the length of the amplifier at any time t and is given by $S(t,z) = S(t,0)G(t,z)$, where $G(t,z) = \mathrm{e}^{g_m(t,z)}$ is the single-pass gain and $g_m(t,z) = h_{\mathrm{N}} + h_{\mathrm{SHB}} + h_{\mathrm{CH}}$. The carrier lifetime, SHB and CH relaxation times of the electrons are represented by τ_{s}, τ_{SHB} and τ_{CH}, respectively. The gain compression coefficients correponding to SHB and CH are $\varepsilon_{\mathrm{SHB}}$ and $\varepsilon_{\mathrm{CH}}$, respectively. The total phase variation of the pulse due to both the interband and intraband effects (only CH) is given by

$$\phi(t,z) = \phi(t,0) - \frac{1}{2}\alpha_{\mathrm{N}}[h_{\mathrm{N}} - g_0(z)] - \frac{1}{2}\alpha_{\mathrm{CH}}h_{\mathrm{CH}}, \tag{2}$$

where $\phi(t,0)$ is the input phase of the pulse and α_{N} and α_{CH} are respectively the phase-amplitude coupling coefficients arising due to carrier recombination and CH effects. The spectrum of the output pulse is obtained by taking the Fourier transform of the output pulse. The material and geometrical parameters of the SOA used in the simulation are listed in table 1, most of which are taken from [9].

Table 1. Values of the parameters of a bulk InGaAsP SOA [9].

Symbol	Meaning	Value	Unit
Γ	Confinement factor	0.33	
d	Thickness of the active region	0.250	μm
w	Width of the active region	3.0	μm
L	Length of the active region	1200	μm
τ_{s}	Carrier lifetime	240	ps
τ_{SHB}	SHB relaxation time	60	fs
τ_{CH}	CH relaxation time	530	fs
$\varepsilon_{\mathrm{CH}}$	CH nonlinear gain compression factor	3.0×10^{-23}	m^3
$\varepsilon_{\mathrm{SHB}}$	SHB nonlinear gain compression factor	1.5×10^{-23}	m^3
α_{N}	Phase-amplitude coupling coefficient	10	
α_{CH}	Phase-amplitude coupling coefficient due to CH	4.4	
n_{g}	Group index	3.56	
λ	Pulse wavelength	1564	nm

3. Results and discussions

With the help of eqs (1) and (2) and using the SOA parameters enlisted in table 1, we simulate the effect of CH and SHB on a Gaussian pulse propagating through the SOA active region for different pulse width and input pulse energies. If we

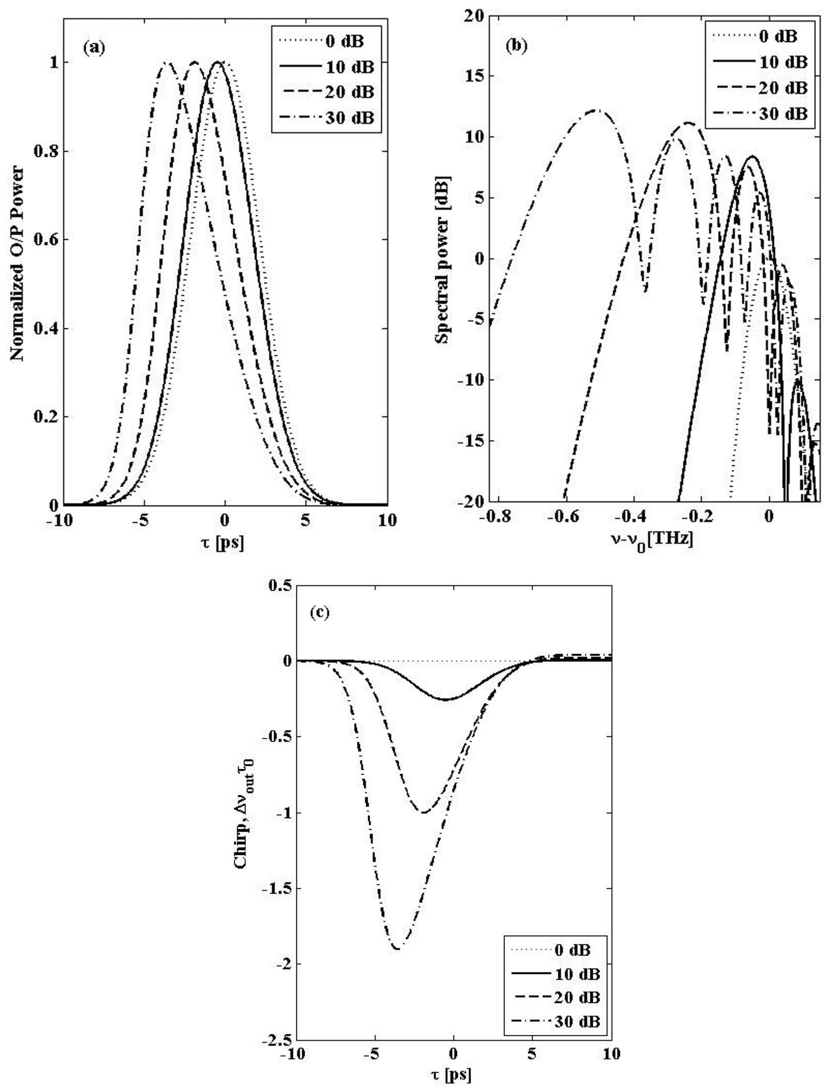

Figure 1. Variation of output pulse shape (**a**), output pulse spectra (**b**) and chirp on the output pulse (**c**) for different unsaturated gain $G_0 = 10$ dB, 20 dB and 30 dB, respectively. The curve for $G_0 = 0$ dB corresponds to the input Gaussian pulse with 5 ps width and $0.1E_s$ energy. The curves are simulated by neglecting the intraband effects.

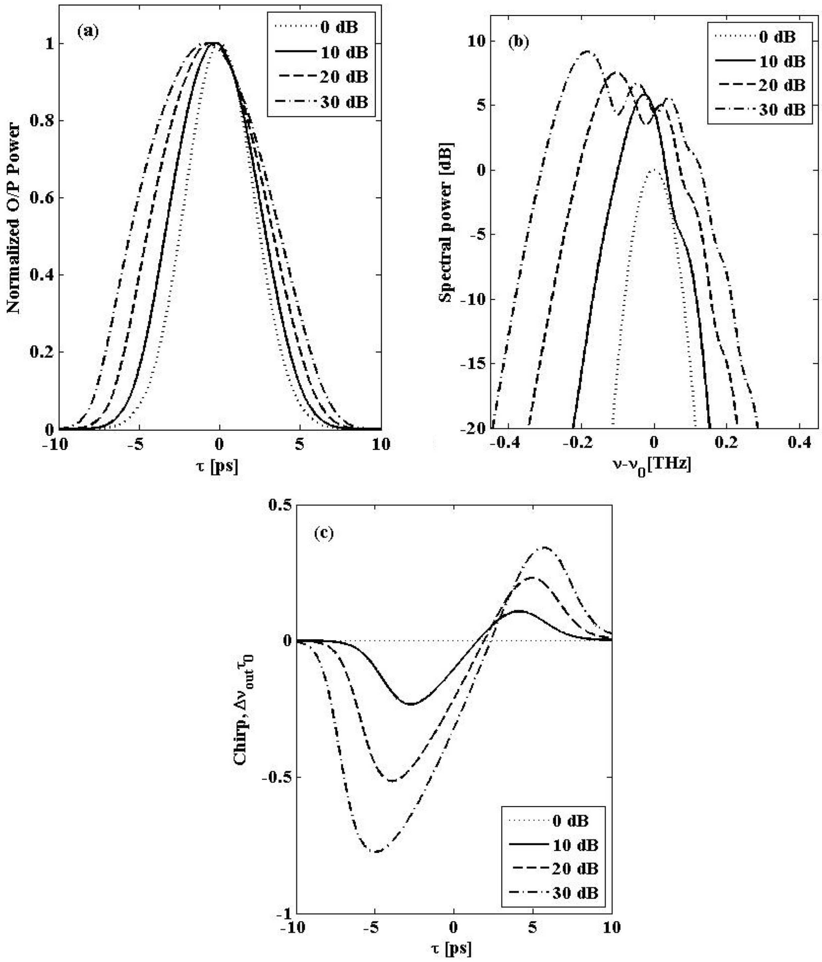

Figure 2. Variation of output pulse shape (**a**), output pulse spectra (**b**) and chirp on the output pulse (**c**) for different unsaturated gain $G_0 = 10$ dB, 20 dB and 30 dB, respectively. The Gaussian input pulse (dotted curve for $G_0 = 0$ dB) width is 5 ps and energy is $0.1E_\mathrm{s}$. The curves are simulated by considering the intraband effects.

neglect the intraband effects in the SOA, which will be the case when the pulse width is larger than the intraband relaxation times, then we only need to solve eq. (1a). By numerically solving it for a Gaussian pulse of 5 ps pulse width and with an energy 0.1 times that of the saturation energy ($E_\mathrm{s} = 4.1$ pJ) of the SOA, we obtain the pulse shape, spectrum and chirp of the output pulse shown in figure 1. The results match well with those predicted in [3] where the equation was solved analytically. Figure 1a shows the output pulse deformation for a Gaussian pulse for unsaturated gain of 10 dB, 20 dB and 30 dB, respectively. Figures 1b and 1c show the corresponding output pulse spectra and chirp.

From figure 1 it is clear that increasing the gain of the amplifier increases the deformation and spectral distortion of the output pulse for the same input pulse width and energy. The chirping on the output pulse is also increased. When the pulse energy exceeds the saturation energy, the output pulse shape as well as the spectrum are highly deformed. Considering the intraband effects for the same pulse parameters as in figure 1, we find that the output pulse shape is less deformed after amplification but there is an overall broadening of the pulse with increasing amplifier gain (see figure 2a). This is due to the intraband gain which rebuilds quickly within the time of a single pulse as carrier relaxation time is much smaller than the pulse width.

Figure 2b shows the output spectrum of the amplified signal when intraband effects are considered. In this case, the spectrum is less asymmetric with a red-shift but the spectral width is reduced, when compared with figure 1b. This may be because of the fact that the output pulse is almost uniformly broadened due to the intraband fast gain process. Figure 1c shows the negative chirping introduced throughout the pulse due to interband gain modulation. By including intraband effects it is found that there is also a positive chirping at the trailing edge of the pulse which is due to the fast recovering nonlinear gain (see figure 2c). This simulation result accounts for the experimental observation in ref. [2]. The amount of chirping is reduced by 60% with respect to the first case. As the pulse width decreases the intraband effects become more pronounced.

4. Conclusions

We have discussed the modelling of an SOA for ultrashort pulse propagation by considering the intraband effects and compared it with the case when they are neglected. The simulation results show that due to the CH effect the gain of the amplifier recovers quickly resulting in lower distortion of the output pulse shape, spectrum and less chirping in the output pulse.

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