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Rising and falling time of amplified picosecond optical pulses by semiconductor optical amplifiers

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Abstract

After adopting the theoretical model that includes several physical mechanisms such as the position- and time-dependent carrier lifetime, the gain saturation caused by the depletion of carrier density owing to the stimulated emission, the gain compression induced by the intraband process of carrier heating and spectral hole burning, the gain asymmetry and shift, both the rising and falling time of amplified picosecond optical pulses by the semiconductor optical amplifiers (SOAs) have been investigated numerically. The results show that with the increase of the bias current of SOAs or the length of SOAs, the rising time will decrease and the falling time increase; the input pulse with a large peak power will accelerate the rising time shortening and the falling time lengthening; the gain compression has an obvious influence on the rising and falling time for several picosecond width input pulses and gives approximately no effect for the input pulses in the tens of picosecond range; the gain asymmetry and shift affects the rising and falling time.

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Keywords: Semiconductor optical amplifiers; Picosecond optical pulses; Rising and falling time

1. Introduction

With the development of semiconductor technology, the semiconductor optical amplifiers (SOAs) have been largely improved in performances and received considerable attention due to their potential applications in optical fiber communication systems as high-speed switching, all-optical wavelength conversion, $2R$ or $3R$ regeneration, in-line amplification etc. Accordingly, the dynamic response of the SOA to ultra-short optical pulses has therefore been a key subject and has been extensively investigated both theoretically and experimentally [1–7]. Even so, we have noticed that most of the relevant reports focus on the gain dynamics or pulse evolution, and few pay special concentrations on the asymmetry of the amplified optical pulses though some phenomena may be

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hidden in relevant researches [8,9]. The rising time (defined as the time that the amplitude of the amplified pulse by SOA increases from 10% to 90% of the amplified pulse peak at the leading edge) and falling time (defined as the time that the amplitude of the amplified pulse by SOA decreases from 90% to 10% of the amplified pulse peak at the tailing edge) are useful to quantify the degree of the pulse asymmetry for the amplified pulse being single peak contribution. (In fact, we discover, through calculations, that this condition can usually be satisfied for the input pulse with a peak power no more than about 1 W. However, if the input pulse has a larger peak power, the amplified pulse will be distorted obviously and appear multi-peak contribution. Under this circumstance the rising and falling times may not be suitable for characterizing the pulse.) Based on above considerations, the rising and falling times are investigated numerically for input pulses with different width and peak power or for the SOA with different bias current and length. Regardless of the complications of the amplified process of ultra-short optical pulses by SOAs, the theory modeling the dynamic process has been gradually improved in last ten years. The initial model for describing pulse amplification of SOA is presented by Agrawal and Olsson where the gain saturation of the SOA caused by the depletion of carrier density owing to the stimulated emission was included [1], and then was developed after taking into account the gain compression induced by intraband process of carrier heating and spectral hole burning [2–4], gain asymmetry and shift [4,10,11], position- and time-dependent carrier lifetime [10,11,13]. Nevertheless, few studies adopt a model that includes all above mechanisms due to the difficulty of the numerical simulations. In this paper, a relatively complete model has been used after overcoming the simulative problem and then how these mechanisms affect the rising and falling time of amplified picosecond optical pulses can be specified.

2. Theory

Assuming that the reflectivity of both facets of SOA are equal to zero, after synthesizing the theoretical model mentioned above, the rate equations describing a optical pulse amplification by SOAs can be written as

$$\frac{\partial N(z,T)}{\partial T} = \frac{I}{eV} - F(N) - \frac{g_{\mathrm{m}}(z,T)}{\hbar\omega\sigma}P(z,T), \qquad (1)$$

$$\frac{\partial P(z,T)}{\partial z} = g_{\mathrm{m}}(z,T)P(z,T) \qquad (2)$$

and

$$F(N) = AN + BN^2 + CN^3 = N/\tau_{\mathrm{c}}, \qquad (3)$$

where N is the carrier density, T ($= t - z/v_{\mathrm{g}}, v_{\mathrm{g}}$ is the group velocity in the SOA) is measured in a reference frame moving with the pulse, I is the injection current, e is the electron charge, V is the volume of the active layer, $\hbar\omega$ is the photon energy, σ is the cross-sectional area of the active layer, P is the optical power, A, B, and C (their values usually vary with different SOAs and should be determined by comparison with experiments) characterize the nonradiative recombination, the spontaneous emission and the Auger process, respectively, τ_{C} is the position- and time-dependent carrier lifetime which sometimes is regarded as a constant in order to simplify the simulation (a comparison of the amplified pulse between the position- and time-dependent carrier lifetime and the constant carrier lifetime can be seen in [13], where a obvious difference can be observed), g_{m} is the gain coefficient and can be expressed by

$$g_{\mathrm{m}}(z,T) = \frac{\Gamma g(N)}{1 + \varepsilon P(z,T)}, \qquad (4)$$

where Γ is the confinement factor, ε is the gain compression factor which is phenomenologically introduced to describe the effects of the carrier heating and spectral hole burning, and

$$g(N) = a(N - N_0) - a_1(\lambda - \lambda_N)^2 + a_2(\lambda - \lambda_N)^3. \qquad (5)$$

Here, a is the differential gain coefficient, a_1 and a_2 are empirically determined constants and characterize the width and asymmetry of the gain profile, N_0 is the transparency carrier density, λ_N describes the shift of the gain peak, which is represented by

$$\lambda_N = \lambda_0 - a_3(N - N_0), \qquad (6)$$

where λ_0 is the gain peak wavelength at transparency, and a_3 is a empirical constant showing the shift of the gain peak.

Based on Eqs. (1)–(6), the temporal shape of amplified pulse for a given input pulse passing through a SOA can be simulated numerically (the detailed method is not involved in this Letter due to the limited space), and both the rising and falling times can be investigated thus far.

3. Results and discussion

For simplicity, the input pulse is supposed to be a Gaussian profile with $P_{in}\exp[-(T/T_0)^2]$, where P_{in} is the peak power, T_0 characterizes the pulse width. Furthermore, the input pulse is assumed to be a single-frequency light (the central wavelength is equal to 1.55 μm), which is reasonable because a picosecond pulse has a relative narrow spectral width compared with the bandwidth of the SOA. The used data in calculations are: $L = 0.50 \times 10^{-3}$ m, $\sigma = 0.18 \times 10^{-12}$ m^2, $a = 2.5 \times 10^{-20}$ m^2, $a_1 = 7.4 \times 10^{18}$ m^{-3}, $a_2 = 3.155 \times 10^{25}$ m^{-4}, $a_3 = 3\times 10^{-32}$ m^4, $\varepsilon = 0.2$ W^{-1}, $N_0 = 1.1 \times 10^{24}$ m^{-3}, $A = 1.5\times 10^8$, $B = 2.5 \times 10^{-17}$ m^3 s^{-1}, $C = 9.4 \times 10^{-41}$ m^6 s^{-1}, the values for A, B, and C are based on [10], $\Gamma = 0.3$, $\lambda_0 = 1.55$ μm.

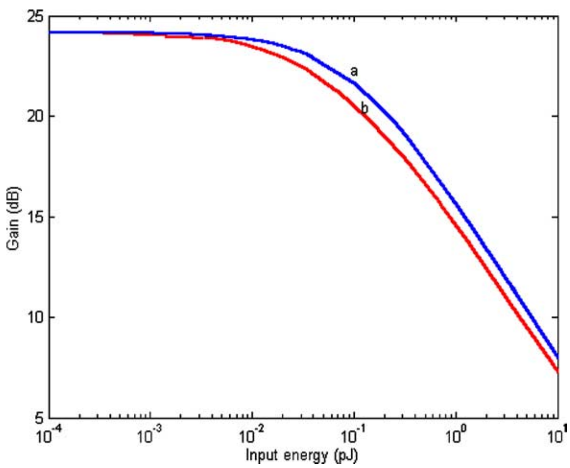

Fig. 1. Amplifier gain versus input energy for the bias current of the SOA $I = 100$ mA with pulse widths $T_0 = 20$ ps (curve a) and 2 ps (curve b), respectively.

Fig. 1 shows the resulting saturation characteristics by plotting gain versus input energy for the bias current of the SOA $I = 100$ mA and the input pulse widths $T_0 = 20$ ps (curve a) and 2 ps (curve b), respectively, where all the physical mechanisms mentioned above have been included. Clearly, the 3-dB saturation energy (defined as the input energy for which the gain is half the unsaturated value) is lower for 2 ps as compared to 20 ps pulse. The reason that results in the difference is mainly due to the gain compression. Calculations show that if neglecting the gain compression, the difference is negligible.

In Fig. 2, the variations of the rising and falling time with the bias current of the SOA have been plotted for $P_{in} = 10$ mW after focusing on different physical mechanisms, where in figure (a) $T_0 = 20$ ps and in (b) $T_0 = 2$ ps, respectively. From this diagram, it can be seen, as expected, that the rising time of the amplified pulse by SOA is usually shorter than that of the input pulse and the falling time is longer than that of the input pulse; with the increase of the bias current of the SOA, the rising time further shortens and the falling time further lengthens. These behaviors observed are well known and are mainly due to the gain saturation induced by the depletion of the carriers owing to the stimulated emission, as observed in [1]. The gain compression caused by the carrier heating and the spectral hole burning slows down the rising time shortening and the falling time lengthening. For an input pulse with several picoseconds width, the effect of the gain compression is evident, as already seen in [2]. For an input pulse in the tens of picosecond width, the effect of the gain compression is slight owing to a relative small characteristic time (50–100 fs for spectral hole burning and 700–1.3 ps for carrier heating) of these intraband processes, which is similar to the result of [3]. From this diagram, it can also be concluded that the gain asymmetry and shift of the SOA, which has been considered in wavelength conversion or WDM systems [10–12] and however is not, to our knowledge, included in investigating the temporal change of the pulse by the SOA, has an important influence on the rising and falling time. The effect of the gain asymmetry and shift depends on the input pulse wavelength and the gain distribution of

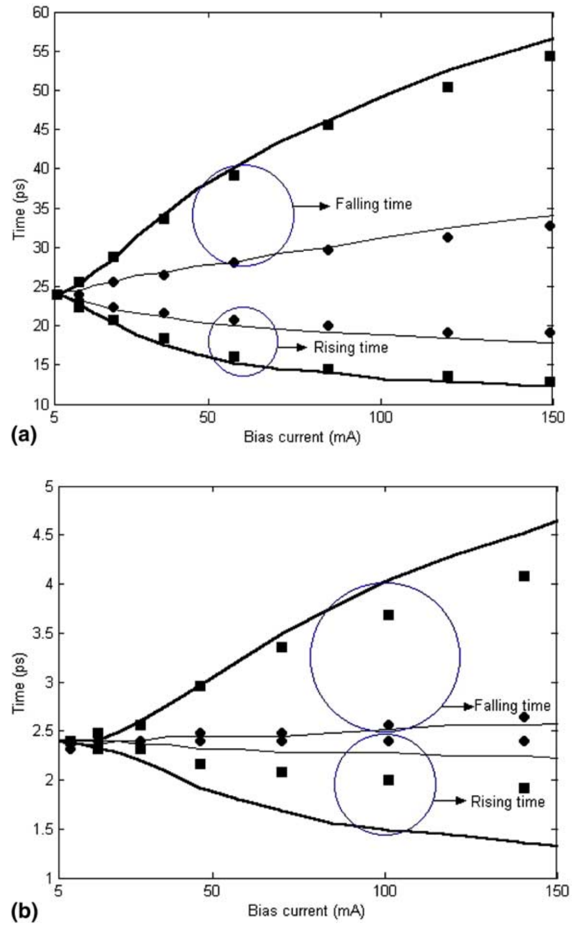

Fig. 2. Variation of the rising and falling time with the bias current of the SOA for $P_{in} = 10$ mW after focusing on different physical mechanisms: (–), without gain compression, gain asymmetry and shift (i.e., ε, a_1, a_2 and a_3 are taken as zero); (■), with gain compression, without gain asymmetry and shift (i.e., ε has a value, a_1, a_2 and a_3 are taken as zero); (–), without gain compression, with gain asymmetry and shift (i.e., $\varepsilon = 0, a_1, a_2$ and a_3 have values); (●), with gain compression, gain asymmetry and shift (i.e., ε, a_1, a_2 and a_3 have values), where in figure (a) $T_0 = 20$ ps and in (b) $T_0 = 2$ ps, respectively.

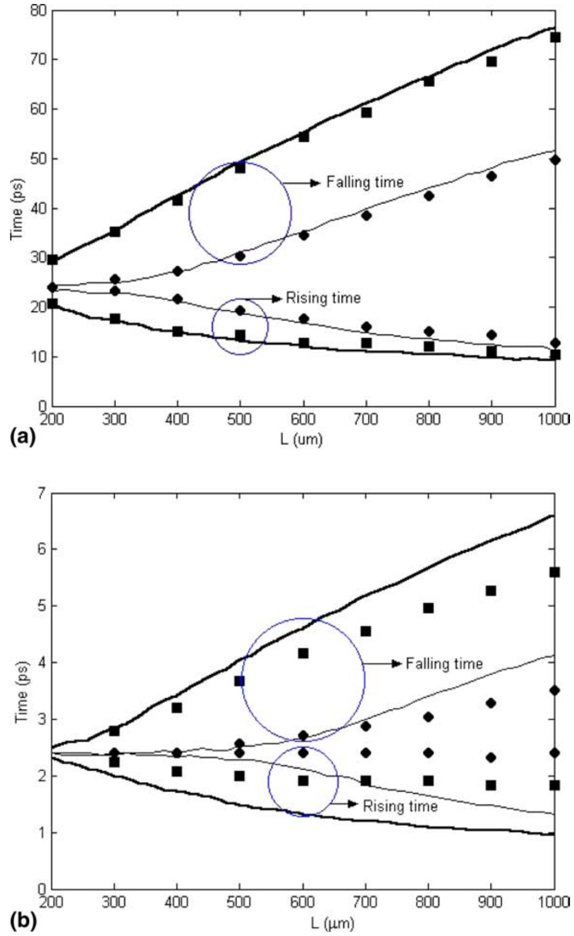

Fig. 3. Variations of the rising and falling time with the length of SOA for $N = 4.0 \times 10^{24}$ m^{-3}, $P_{in} = 10$ mW, where in figure (a) $T_0 = 20$ ps and in (b) $T_0 = 2$ ps, respectively.

the SOA. In this paper, the input pulse wavelength and the gain peak wavelength at transparency have been taken as 1.55 μm. As a result, with the increase of the bias current from the transparency current, since the gain profile shifts to short wavelengths, the acquired gain of the input pulse will reduce compared to the case where the gain asymmetry and shift is not considered, which inevitably weakens the gain saturation effect and then slows down the rising time shortening and the falling time lengthening with the increase of the bias current.

In Fig. 3, the variations of the rising and falling time with the length of SOA have been plotted under different physical mechanisms for $N = 4.0 \times 10^{24}$ m^{-3}, $P_{in} = 10$ mW, where in figure (a) $T_0 = 20$ ps and in (b) $T_0 = 2$ ps, respectively. From this diagram, it can be seen that with the increase of the length of the SOA, the rising time shortens and the falling time lengthens, as showed in [9]. Because in calculations the carrier density N maintains a constant, enlarging the SOA's length is equivalent to fix the length of the SOA and increase the biased current of the SOA, then a similar tendency to Fig. 2 can be observed.

It is well known that the input pulse peak power severely affects the amplified process. In Fig. 4, for the bias current of the SOA $I = 100$ mA, the dependence of the rising and falling time on the input pulse peak power has been shown after considering different physical mechanisms, where in figure (a) $T_0 = 20$ ps and in (b) $T_0 = 2$ ps, respectively. From this diagram, it can be found that with the increase of the input pulse peak power, the rising time of the amplified pulse shortens and the falling time lengthens, which is because the increase of the

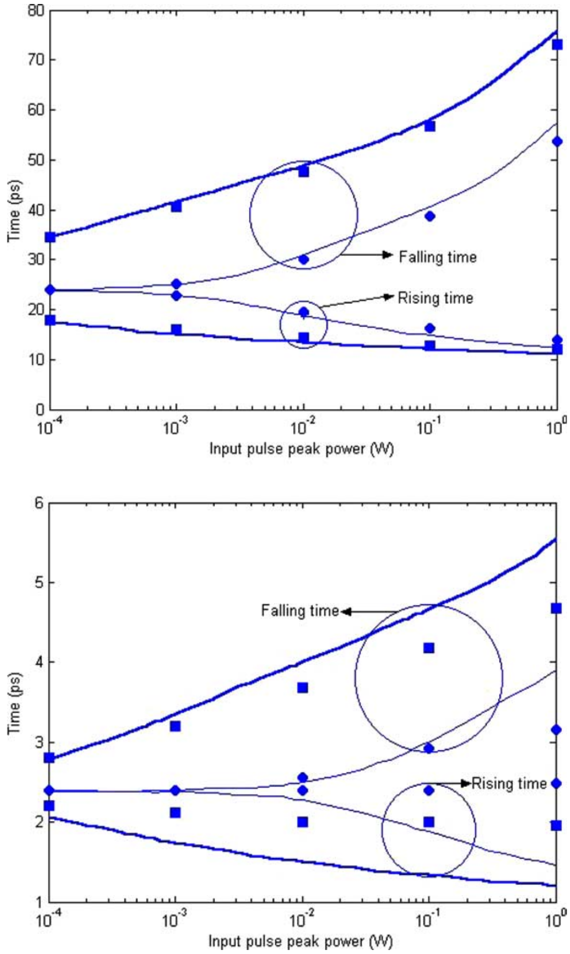

Fig. 4. Dependence of the rising and falling time on the input pulse peak power after considering different physical mechanisms for $I = 100$ mA, where in figure (a) $T_0 = 20$ ps and in (b) $T_0 = 2$ ps, respectively.

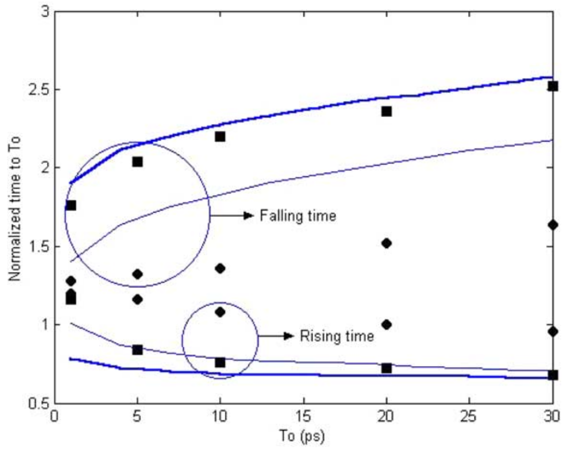

Fig. 5. Rising and falling time (normalized to T_0) vs. T_0 under different physical mechanisms for $I = 100$ mA, $P_{in} = 10$ mW.

input power peak power speeds the gain saturation effect. At the meantime, for an input pulse with several picoseconds width, the effect of the gain compression enhances with the increase of the input pulse peak power. If one neglects the gain compression, the gain asymmetry and shift, and compares the results with the case including the gain compression, without the gain asymmetry and shift, an approximate 0.8 ps difference of the rising time for $P_{in} = 1$ W can be seen [3].

From above results and [2,3], one can predict that the input pulse width of course takes an effect on the rising and falling time. In Fig. 5, the rising and falling time (normalized to T_0) vs. T_0 have been shown under different physical mechanisms for $I = 100$ mA, $P_{in} = 10$ mW. From this diagram, it can be seen that a wider pulse raises slightly the shortening degree of the rising time and raises largely the lengthening degree of the falling time. Also, a wider pulse weakens the effect of the gain compression, which is in agreement with general insights on the gain compression [2,3].

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