Energy limits imposed by two-photon absorption for pulse amplification in high-power semiconductor optical amplifiers

Faisal R. Ahmad, Yen Wei Tseng, Mikhail A. Kats, and Farhan Rana*

School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14850, USA
**Corresponding author: fr37@cornell.edu*

Received January 23, 2008; accepted March 25, 2008;
posted April 7, 2008 (Doc. ID 92017); published May 7, 2008

We study the combined effects of dynamic gain saturation and two-photon absorption on the amplification of short pulses in semiconductor optical amplifiers and show that two-photon absorption can saturate the amplifier gain and limit the output pulse energies even for amplifiers with large gain saturation energies. We discuss the upper limits for the pulse energies obtainable from semiconductor optical amplifiers in the presence of two-photon absorption and show that for single transverse mode waveguide amplifiers these upper limits can range from values as small as a few picojoules to several hundred picojoules for pulse widths in the 0.5 ps to 20 ps range, respectively. © 2008 Optical Society of America

OCIS codes: 250.5980, 320.7110, 250.5530.

There has been a growing interest in obtaining high-energy short pulses from semiconductor optical amplifiers (SOAs) and from semiconductor mode-locked lasers [1–4]. Schemes employed to generate high-energy pulses from SOAs have shared one common goal: to reduce dynamic gain saturation in the amplifier by either increasing the effective optical mode area and reducing the overlap of the mode with the active region, as in the slab-coupled waveguide structures reported in [3,4], or by increasing the cross-sectional area of the entire device, as in the flared or tapered waveguides reported in [1,2]. In this context the questions that arise are (i) what are the limits, if any, on the maximum pulse energies obtainable from SOAs and (ii) what scaling schemes can be used to produce very high pulse energies from SOAs. The answer to the first question depends on the pulse width. In this Letter, we limit the discussion to pulses that are long enough (>0.5 ps) such that carrier intraband relaxation and carrier heating do not significantly affect pulse gain [5]. We study the combined effects of dynamic gain saturation and two-photon absorption (TPA) on pulse amplification in SOAs. TPA, in addition to dynamic gain saturation, can limit the maximum pulse energies obtainable from SOAs. The fact that TPA introduces loss for optical pulses in SOAs is recognized and well understood, and its effects have been included in several numerical simulation results reported earlier [6]. However, to the best of our knowledge, the limitations imposed by TPA on the maximum pulse energies obtainable from SOAs have never been quantified.

For dynamic gain saturation, the pulse gain saturation energy E_{sat} determines the maximum pulse energies obtainable from a SOA without significantly compromising the amplifier gain. E_{sat} equals $\hbar\omega_o A_{\text{eff}}/(\mathrm{d}g/\mathrm{d}N)$, where ω_o is the pulse center frequency, $\mathrm{d}g/\mathrm{d}N$ is the material differential gain, and A_{eff} is the effective area of the optical mode. $A_{\text{eff}} = A/\Gamma$, where A is the active region cross-sectional area and Γ is the confinement of the mode in active region. A useful pulse energy scale E_{TPA} emerges from our analysis that determines the maximum pulse energies obtainable from a SOA under limitations imposed by TPA. We show here that in high-power SOAs when Γ is reduced to increase A_{eff} and E_{sat}, E_{TPA} is reduced and the pulse energies can become limited by TPA. The results presented here could explain the difficulty in obtaining very short pulses from mode-locked lasers employing high-power slab-coupled waveguide optical amplifiers [3,4]. We assume a pulse with envelope $A(z,t)$, normalized such that the pulse energy $E(z)$ equals $\int_{-\infty}^{\infty}|A(z,t)|^2\mathrm{d}t$. The equation governing pulse propagation in the SOA can be written as [7]

$$\frac{\partial A(z,t)}{\partial z} = -j\frac{\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial t^2} + \frac{\Gamma}{2}g(z,t)(1-j\alpha)A(z,t) - \frac{l}{2}A(z,t) + \frac{(jk_o n_2 - \beta/2)}{A_{\text{mode}}}|A(z,t)|^2 A(z,t). \tag{1}$$

Here, β_2 is the dispersion, Γ is the mode gain confinement factor, $g(z,t)$ is the time-dependent material gain, α is the linewidth enhancement factor, l is the waveguide linear loss, n_2 is the material intensity dependent refractive index, k_o is the free-space propagation vector at the pulse center frequency ω_o, and β is the material TPA coefficient. A_{mode} is related to the mode area. If the waveguide transverse mode field is given by $\phi(x,y)$, then $A_{\text{mode}} = (\int\int|\phi(x,y)|^2\mathrm{d}x\mathrm{d}y)^2/\int\int|\phi(x,y)|^4\mathrm{d}x\mathrm{d}y$. Note that A_{mode} can be substantially different from A_{eff}. Under the assumptions that the material gain varies linearly with the carrier density and that the pulse width is much smaller than the gain relaxation time, the time-dependent gain $g(z,t)$ is [7] $g(z,t) = g_o\exp(-\int_{-\infty}^{t}|A(z,t')|^2\mathrm{d}t'/E_{\text{sat}})$, where E_{sat} is the pulse gain saturation energy and g_o is the unsaturated material gain just before the pulse. This expression is substituted in Eq. (1) to obtain the following exact equation for the pulse energy $E(z)$:

$$\frac{\mathrm{d}E(z)}{\mathrm{d}z} = \Gamma g_o E_{\mathrm{sat}}\left[1 - \exp\left(-\frac{E(z)}{E_{\mathrm{sat}}}\right)\right] - lE(z) - \gamma(z)E^2(z). \tag{2}$$

The above equation gives rise to two different gain saturation mechanisms, both of which are discussed below. $\gamma(z)$ models the nonlinear loss owing to TPA. $\gamma(z)$ is related to the material TPA coefficient β as

$$\gamma(z) = \frac{\beta}{A_{\mathrm{mode}}}\frac{\int |A(z,t)|^4 \mathrm{d}t}{\left(\int |A(z,t)|^2 \mathrm{d}t\right)^2}. \tag{3}$$

For a pulse with a Gaussian intensity profile and FWHM pulse width τ, $\gamma \approx \beta/(A_{\mathrm{mode}}1.5\tau)$. The pulse width and shape are not constants and can change during propagation [6,8]. Although a complete discussion of these effects is beyond the scope of this Letter, full numerical simulations of Eq. (1) show that if the value of γ is assumed to be a constant, then the pulse energies at the output of the amplifier predicted by Eq. (2) are accurate to within 5%, provided the value of γ used is the average value of $\gamma(z)$ over the length of the amplifier. In the discussion that follows, γ will be assumed to be a constant and, therefore, the pulse width τ should be understood as the average width of the pulse in the amplifier in the sense of Eq. (3).

We define the input pulse energy E_{in} as $E(z=0)$ and, if L is the length of the SOA, the output pulse energy E_{out} as $E(z=L)$. In the absence of TPA (i.e., $\gamma=0$) and when $E(z) \ll E_{\mathrm{sat}}$, the unsaturated SOA gain equals $E_{\mathrm{out}}/E_{\mathrm{in}} = \exp[(\Gamma g_o - l)L]$. For numerical simulations we use parameters that correspond to a high-power InGaAsP/InP slab-coupled waveguide amplifier similar to the one reported in [3]. The values of L, Γ, l, E_{sat}, and A_{mode} are 0.8 cm, 0.003, 0.7 cm^{-1}, 100 pJ, and 14 $\mu\mathrm{m}^2$, respectively [3]. The value of the TPA coefficient β in most direct bandgap III-V semiconductors, such as GaAs and InP, is in the 20–40 $\times 10^{-9}$ cm/W range and is only weakly wavelength dependent for wavelengths corresponding to energies slightly below the bandgap to energies slightly above the bandgap [9]. Assuming values of β and FWHM pulse width equal to 35×10^{-9} cm/W and 10 ps, respectively, Fig. 1 shows the E_{out} versus E_{in} curves in the absence (dashed curve) and presence of TPA for pulse widths of 10 ps (solid curve) and 1 ps (dotted–dashed curve). In each case, the three curves correspond to three different values of the unsaturated material gain g_o (800, 1200, and 1600 cm^{-1}). Figure 2 plots the corresponding amplifier gain values (in decibels) as a function of the output pulse energy E_{out}. In the absence of TPA, the SOA gain saturates by ~3 dB for output pulse energies close to E_{sat}. In the presence of TPA, the SOA gain saturates at much smaller output pulse energies.

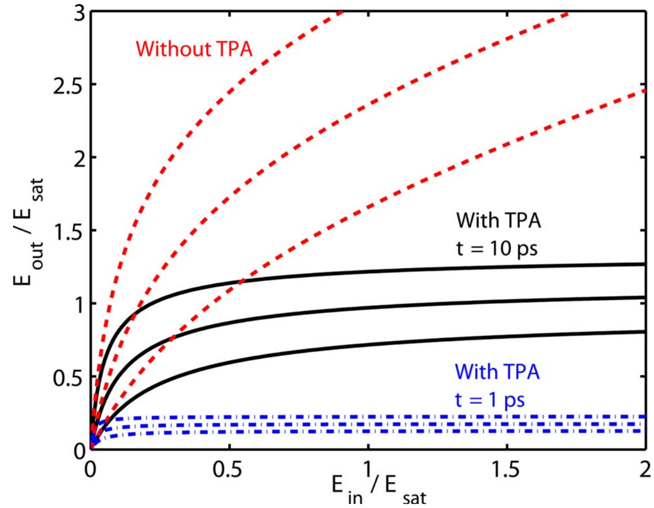

Fig. 1. (Color online) E_{out} versus E_{in} curves without TPA (dashed curve) and with TPA assuming FWHM pulse widths of 10 ps (solid curve) and 1 ps (dashed–dotted curve). The SOA parameters are given in the text and correspond to the InGaAsP SOA in [3]. $E_{\mathrm{sat}}=100$ pJ. In each case, the three curves correspond to unsaturated material gain values (g_o) of 800, 1200, and 1600 cm^{-1}.

The maximum output pulse energy E_{TPA} for which the SOA gain saturates by ~3 dB owing to TPA instead of dynamic gain saturation can be estimated using Eq. (2):

$$E_{\mathrm{TPA}} = \frac{\Gamma g_o}{e\gamma} \approx \frac{\Gamma g_o 1.5\tau A_{\mathrm{mode}}}{e\beta}. \tag{4}$$

If $E_{\mathrm{sat}} \ll E_{\mathrm{TPA}}$, then dynamic gain saturation will saturate the SOA gain for large pulse energies, and if $E_{\mathrm{sat}} \gg E_{\mathrm{TPA}}$, then TPA will saturate the SOA gain for large pulse energies. If E_{sat} and E_{TPA} are of the same

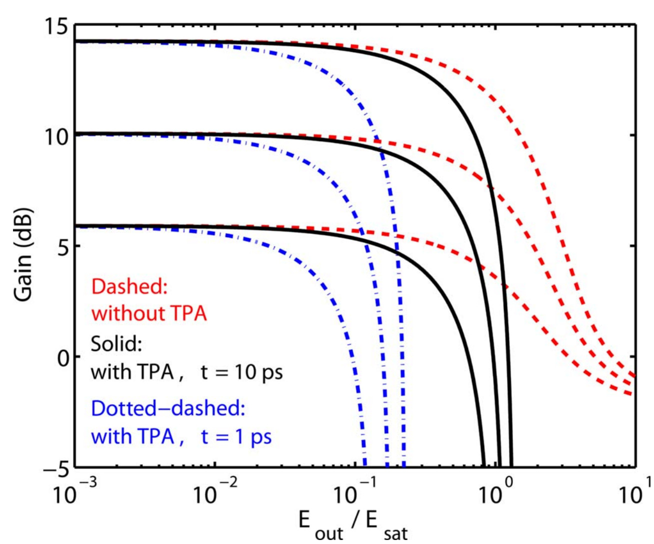

Fig. 2. (Color online) SOA gain without TPA (dashed curves) and with TPA assuming FWHM pulse widths of 10 ps (solid curves) and 1 ps (dotted–dashed curves). The SOA parameters are given in the text and correspond to the InGaAsP SOA in [3]. $E_{\mathrm{sat}}=100$ pJ. In each case, the three curves correspond to unsaturated material gain values (g_o) of 800, 1200, and 1600 cm^{-1}.

order, then both TPA and dynamic gain saturation will play a role in saturating the SOA gain. The values of E_{TPA} for the SOA whose characteristics are shown in Figs. 1 and 2, for a pulse width of 10 ps, are 53, 79, and 106 pJ for unsaturated material gain values of 800, 1200, and 1600 cm^{-1}, respectively. Since E_{TPA} is of the same order as E_{sat}, both TPA and dynamic gain saturation play a role in saturating the SOA gain for a 10 ps pulse width. If one assumes a pulse width of 1 ps, the values of E_{TPA} for the same unsaturated material gain values are 5.3, 7.9, and 10.6 pJ, respectively, which are much less than the value of E_{sat} (=100 pJ). In this case, the SOA gain is saturated by TPA, as shown in Figs. 1 and 2. The parameter E_{TPA} is therefore a useful energy scale for determining the performance of an SOA for high-energy short-pulse amplification. In Fig. 3, the value of E_{TPA} is plotted as a function of the pulse width for different values of the unsaturated material gain g_o. The values of A_{mode}, β, and l are as given above and correspond to the slab-coupled waveguide SOA in [3]. For pulse widths longer than 10 ps, $E_{\mathrm{TPA}} > E_{\mathrm{sat}}$, and dynamic gain saturation limits the maximum achievable pulse energies. For shorter pulse widths, $E_{\mathrm{TPA}} < E_{\mathrm{sat}}$ and TPA limits the maximum achievable pulse energies.

It should be noted here that SOA waveguides with smaller values of modal gain per unit length are more susceptible to gain saturation driven by TPA. Since most III-V semiconductor materials can produce maximum material gain values in the neighborhood of 1500–1800 cm^{-1}, the two main design handles available to increase the value of E_{TPA} for high-energy short-pulse amplification in SOAs are the mode gain confinement factor Γ and the mode area A_{mode}. The scaling of the product ΓA_{mode} with waveguide geometry is not trivial, since an increase in the mode area can lead to a decrease in the confinement factor and vice versa, and this is the case for the slab-coupled waveguide amplifiers in [3,4]. In fact, whereas the values of E_{sat} in slab-coupled waveguide structures are much larger compared with the values in conventional SOA waveguide structures [3,4], the values of E_{TPA} in slab-coupled waveguide structures are comparable with or even smaller than the values in conventional waveguide structures. For example, a conventional five quantum well, 3 μm wide, InGaAsP/InP waveguide amplifier with A_{mode}, Γ, g_o, and $\mathrm{d}g/\mathrm{d}N$ equal to 1.5 $\mu\mathrm{m}^2$, 0.08, 1600 cm^{-1}, and $7\times10^{-16}\,\mathrm{cm}^2$, respectively, would have $E_{\mathrm{sat}} \approx 2.4$ pJ and $E_{\mathrm{TPA}} \approx 30$ pJ for a pulse width of 1 ps. An optimal waveguide design strategy could involve matching the values of E_{sat} and E_{TPA} for a given pulse width to obtain the maximum output pulse energies. The inverse relationship between E_{sat} and E_{TPA} is not unavoidable. The value of A_{mode} can be increased without much affecting the confinement factor Γ by flaring or tapering a conventional SOA waveguide (i.e., by increasing the waveguide width) as in [1,2]. Although TPA and dynamic gain saturation can both be reduced in flared amplifiers, the price paid is the increased number of transverse optical modes. Single transverse mode waveguide designs to achieve large values for both E_{sat} and E_{TPA} need to be further investigated.

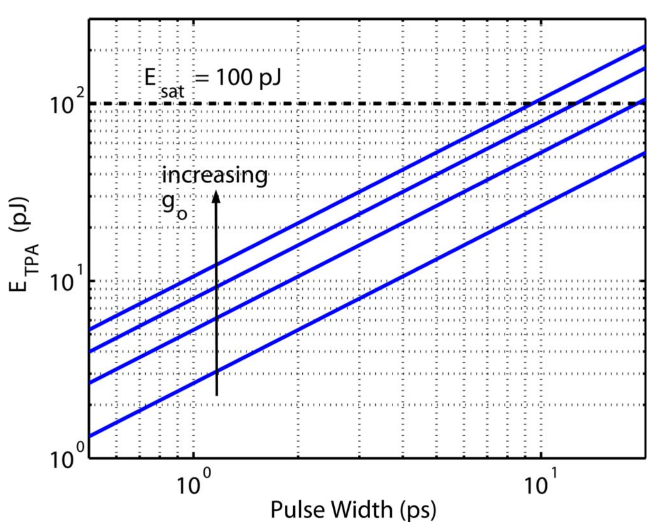

Fig. 3. (Color online) Values of E_{TPA} are plotted as a function of the FWHM pulse width τ. The SOA parameters are the same as in Figs. 1 and 2. The four curves correspond to unsaturated material gain values (g_o) of 400, 800, 1200, and 1600 cm^{-1}.

The authors acknowledge helpful discussions on this paper with Paul W. Juodawlkis. The authors thank Filbert Bartoli for support through the NSF faculty CAREER award, and ILX lightwave Corp., Intel Inc., and Infotonics Inc. for support.

References

1. L. Goldberg, D. Mehuys, and D. Welch, IEEE Photon. Technol. Lett. **6**, 1070 (1994).
2. S. Gee, G. Alphonse, J. Connolly, and P. J. Delfyett, IEEE J. Quantum Electron. **4**, 209 (1998).
3. J. J. Plant, J. T. Gopinath, B. Chann, D. J. Ripin, R. K. Huang, and P. W. Juodawlkis, Opt. Lett. **31**, 223 (2006).
4. F. R. Ahmad and F. Rana, IEEE Photon. Technol. Lett. **20**, 190 (2008).
5. Y. Lai, K. L. Hall, E. P. Ippen, and G. Eisenstein, IEEE Photon. Technol. Lett. **2**, 711713 (1990).
6. M. Y. Hong, Y. H. Chang, A. Dienes, J. P. Heritage, and P. J. Delfyett, IEEE J. Quantum Electron. **30**, 1122 (1994).
7. F. Rana and P. George, IEEE J. Quantum Electron. **43**, 1109 (2007).
8. G. P. Agrawal and N. A. Olsson, IEEE J. Quantum Electron. **25**, 2297 (1989).
9. R. W. Boyd, *Nonlinear Optics* (Academic, 2003).