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# CARRIER-INDUCED GROUP-VELOCITY DISPERSION AND PULSE COMPRESSION IN SEMICONDUCTOR LASER AMPLIFIERS

*Indexing terms: Amplifiers, Optical communication, Semiconductor lasers*

The effect of gain dispersion on pulse amplification in semiconductor laser amplifiers is investigated theoretically. A novel phenomenon, referred to as carrier-induced group-velocity dispersion, is shown to influence considerably the amplified pulse. Chirped input pulses are predicted to be compressed in the presence of carrier-induced dispersion even when the amplifier operates far below saturation. The dependence of the compression factor on device parameters such as the pulse width, the amplifier gain, and the linewidth enhancement factor are studied using a simple analytic model. The results are important for optical communication systems as they imply that semiconductor laser amplifiers can be used to compensate simultaneously for the effects of both fibre loss and fibre dispersion when used as in-line amplifiers.

Semiconductor laser amplifiers have attracted considerable attention$^{1-8}$ as they are capable of providing high single-pass gain (~30 dB) over a wide bandwidth (~5 THz) in the form of a compact and efficient device. For input pulses wider than a few picoseconds input pulses are amplified without significant changes in the pulse shape and spectrum as long as the amplifier operates in the linear regime (no gain saturation).[1,2] When the amplifier operates in the saturation regime, both pulse broadening and narrowing can occur depending on the operating conditions.[7] At the same time, pulse spectrum is considerably broadened[3,4] as a result of the frequency chirp imposed on the amplified pulse by carrier-induced self-phase modulation. Both spectral and temporal changes are attributed to gain saturation.[5,8] For ultrashort input pulses temporal and spectral changes can occur, in principle, even in the linear regime (pulse energy well below the saturation energy) because of gain dispersion. The effects of gain dispersion become particularly important for femtosecond pulses. Such effects have not attracted much attention, partly because an experiment[2] reported distortionless amplification for pulses as short as 3 ps.

This paper shows that both pulse broadening and narrowing can occur in the presence of gain dispersion because of a novel physical phenomenon that appears to remain unnoticed so far. It is referred to here as the carrier-induced group-velocity dispersion (GVD) as it has its origin in the finite gain bandwidth of semiconductor laser amplifiers. More specifically, the frequency dependence of gain results in a frequency dependence of the refractive index because of carrier-induced index changes governed by the linewidth enhancement factor. The resulting contribution to GVD generally exceeds the material contribution and can alter the pulse shape significantly during amplification. Our results show that considerable pulse compression can occur for chirped input pulses as wide as 5 ps even when the pulse energy remains well below the saturation energy of the amplifier.

The starting point of our analysis is the pulse-propagation equation[5]

$$\frac{\partial A}{\partial z} + \frac{1}{v_g}\frac{\partial A}{\partial t} = \tfrac{1}{2}(1 - i\alpha)gA \qquad (1)$$

where $A$ is the slowly varying pulse envelope, $v_g$ is the group velocity, $\alpha$ is the linewidth enhancement factor, and $g$ is the amplifier gain. In the linear regime, gain remains unsaturated, and $g$ is independent of the intensity $|A|^2$. It can, however, still be time dependent for short pulses because of gain dispersion whose role is to reduce the gain for spectral components located far away from the gain peak. If we approximate the gain profile by a parabola in the vicinity of the gain peak, $g(\omega) = g_0[1 - T_2^2(\omega - \omega_0)^2]$, and note that $(\omega - \omega_0)$ is replaced by $i(\partial/\partial t)$ in the time-domain description, $gA$ in eqn. 1 is replaced by

$$gA = g_0 A + g_0 T_2^2(\partial^2 A/\partial t^2) \qquad (2)$$

where $g_0$ is the peak value of the gain and $T_2$ is related to the curvature of the gain profile near the gain peak. We have assumed for simplicity that the carrier frequency of the input pulse coincides with the location of the gain peak. The parameter $T_2$ is analogous to the polarisation relaxation time of a two-level system and is related to the intraband relaxation time in semiconductors with typical values ~0·1 ps. If we define a normalised time $\tau$ in a frame moving with the pulse as

$$\tau = (t - z/v_g)/T_0 \qquad (3)$$

eqns. 1 and 2 can be combined to yield

$$\frac{\partial A}{\partial z} - \tfrac{1}{2}(1 - i\alpha)g_0 d^2\frac{\partial^2 A}{\partial \tau^2} = \tfrac{1}{2}(1 - i\alpha)g_0 A \qquad (4)$$

where $d = T_2/T_0$ is a dimensionless dispersion parameter normalised to the pulse with $T_0$. The parameter $d \ll 1$ for pulses wider than 10 ps but becomes about 0·1 for a 1 ps wide pulse.

The coefficient of the second-derivative term in eqn. 4 is complex, and its imaginary part is responsible for GVD. Since the imaginary part exists only for $\alpha \neq 0$, the existence of GVD is related to carrier-induced index changes governed by $\alpha$. The material contribution to GVD was ignored in writing eqn. 1 as it is negligible for GaInAsP material for input pulses as short as 100 fs. The carrier-induced contribution to GVD generally exceeds the material contribution. One can estimate the importance of carrier-induced GVD by defining the dispersion length, a concept commonly used for optical fibres,[9] through the relation

$$L_D = \frac{T_0^2}{\beta_2^{eff}} = \frac{1}{\alpha g_0 d^2} = \frac{T_0^2}{\alpha g_0 T_2^2} \qquad (5)$$

where $\beta_2^{eff} = \alpha g_0 T_2^2$ is the effective GVD parameter introduced in a manner analogous to that of optical fibres.[9] For $\alpha = 6$, $T_2 = 0{\cdot}1$ ps, and $g_0 = 300\,\mathrm{cm}^{-1}$, we estimate that $\beta_2^{eff} = 18\,\mathrm{ps}^2/\mathrm{cm}$. This value is large enough for carrier-induced GVD to be expected to modify the propagation characteristics of input pulses with $T_0 \sim 1$ ps. As an example, $L_D \approx 500\,\mu m$ for $T_0 = 1$ ps. The effects of GVD are expected to become important if the amplifier length $L$ is comparable to $L_D$. Note that $\beta_2^{eff}$ scales with $T_2$ as $T_2^2$. Since the gain bandwidth $\Delta\nu$ varies as $1/T_2$, $\beta_2^{eff}$ scales as $\Delta\nu^{-2}$ and can increase considerably for amplifiers with a smaller gain bandwidth.

To illustrate the effect of carrier-induced GVD on pulse amplification, we consider the case of chirped Gaussian pulses and take

$$A(0, \tau) = A_0 \exp[-(1 + iC)\tau^2/2] \qquad (6)$$

where $C$ is a chirp parameter.[9] Eqn. 4 can be solved analytically for such input pulses, and the solution is

$$A(L, \tau) = \frac{A_0 \exp[(1 - i\alpha)g_0 L/2]}{(1 + Q)^{1/2}} \exp\left(-\frac{1 + iC}{1 + iQ}\frac{\tau^2}{2}\right) \tag{7}$$

where $Q = d^2 g_0 L(1 - i\alpha)(1 + iC)$. The pulse broadening factor $f_B$, defined as the ratio of the output to input pulse widths, is given by

$$f_B = \left[\frac{1 + 2D(1 + \alpha C) + D^2(1 + \alpha^2)(1 + C^2)}{1 + D(1 + C^2)}\right]^{1/2} \tag{8}$$

where $D = d^2 g_0 L = d^2 \ln(G_0)$. $G_0 = \exp(g_0 L)$ is the single-pass gain of the amplifier for CW input. Fig. 1 shows variation of $f_B$ with $D$ for several values of the chirp parameter $C$ by choosing $\alpha = 6$ as the representative value. Pulse broadening occurs for $C = 0$ (unchirped input pulse) and for positive values of $C$. However, the amplified pulse can exhibit considerable narrowing for negative values of $C$. Such a narrowing is similar to the case of optical fibres[9] which can compress a chirped input pulse (without amplification) as long as $\beta_2 C < 0$. Interestingly, pulses emitted by semiconductor lasers are generally chirped such that $C$ is negative. Such pulses can potentially be amplified and compressed if the amplifier gain $g_0 L$ and the pulse width are optimised to correspond to a value of $d^2 g_0 L$ that corresponds to a minimum in Fig. 1.

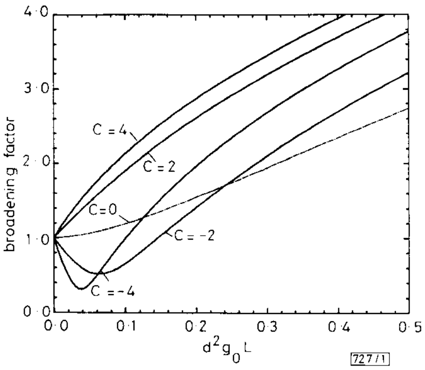

**Fig. 1** *Broadening factor against $d^2g_0L$ for $\alpha = 6$ and several values of the chirp parameter C*

The optimum value $D_{opt}$ of $D = d^2 g_0 L$ can be obtained by setting $\partial f_B/\partial D = 0$ in eqn. 8 and requiring that $f_B$ corresponds to a minimum value $f_B^{min}$. The compression factor defined as $1/f_B^{min}$ is shown in Fig. 2 together with $D_{opt}$ as a function of the chirp parameter $C$. Solid and dashed lines correspond to $\alpha = 6$ and $\alpha = 4$, respectively. The input pulse can be compressed by a factor of more than 6 for large values of $|C|$ and $\alpha$. Pulse compression by a factor of 4 is predicted for typical value $C = -5$ and $\alpha = 6$. More importantly, pulse compression occurs for a relatively small value $D_{opt} = 0{\cdot}02$. Such values of $D_{opt}$ can be realised for $T_0 \approx 2$ ps for amplifiers with 30 dB gain ($g_0 L = 6{\cdot}9$) and $T_2 = 0{\cdot}1$ ps. Input pulses as wide as 5 ps may exhibit significant pulse compression because of carrier-induced GVD. This conclusion applies to both GaAs and GaInAsP amplifiers although the effect is smaller for GaAs amplifiers because of typically smaller values of $\alpha$ observed for this material.

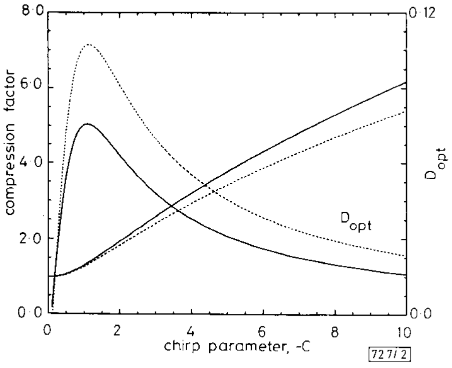

**Fig. 2** *Compression factor against $-C$ under optimum condition*

The optimum value $D_{opt}$ of the dispersion parameter $D = d^2 g_0 L$ is shown on the right-hand scale. Solid and dashed lines correspond to $\alpha = 6$ and $\alpha = 4$, respectively

The results of this paper are important for optical communication systems as they imply that the effects of both fibre loss and fibre dispersion can be compensated simultaneously when semiconductor laser amplifiers are used as in-line amplifiers. In effect, the amplifier not only boosts the peak power but also partially reshapes the input pulse train. It may be possible to cascade several such amplifiers with a proper design. A second application consists of compressing a short optical pulse (~1 ps) with femtojoule energies while at the same time its energy is increased by 20 dB or more. Such weak optical pulses cannot be compressed by conventional techniques as the pulse energy is too small to induce nonlinear index changes.

In conclusion, a novel phenomenon called carrier-induced GVD is shown to influence considerably amplification of short optical pulses in semiconductor laser amplifiers. Its origin lies in the finite gain bandwidth of such amplifiers: Gain dispersion translates into index dispersion through the linewidth enhancement factor. Unchirped input pulses are expected to broaden as a result of carrier-induced GVD. By contrast, chirped input pulses are predicted to undergo considerable compression during amplification. Pulse compression occurs in the linear regime of the amplifier as gain saturation is not required. The effect of gain saturation on pulse shape and spectrum in the presence of carrier-induced GVD requires further study and is under investigation.

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