Effect of carrier depletion on optical phase conjugation in a semiconductor laser amplifier

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The temporal effect of optical phase conjugation in a semiconductor laser amplifier is studied numerically. The conjugate pulse has distortion and frequency chirping owing to the carrier depletion induced by the signal pulse. Both the pulse-shape distortion and frequency chirping are enhanced as the signal power and the injection current increase. We can reduce these two effects by increasing the pump power to reduce the carrier-density depletion induced by the signal pulse.

Recent experiments show that chromatic dispersion can be compensated for by optical phase conjugation (OPC).[1,2] In Ref. 1 OPC was obtained by nondegenerate four-wave mixing (NDFWM) in a dispersion-shifted fiber. In Ref. 2 OPC was obtained by NDFWM owing to the nonlinear gain in a semiconductor laser amplifier (SLA). It has been shown that, by use of dispersion-shifted fiber as a conjugator, there is frequency chirping in the conjugate pulse that is due to the cross-phase modulation between the signal and conjugate pulses.[3] This effect limits the input signal power and hence the output conjugate power. Using a SLA, we will study the distortion and frequency chirping in the conjugate pulse that are due to carrier-density depletion induced by the signal pulse.

An optical wave propagating in the SLA satisfies the equations[4–6]

$$\frac{\partial \phi}{\partial z} = (1/2)\Gamma a(N - N_0)[1 - i\beta - (1 - i\overline{\beta})\epsilon|\phi|^2]\phi - (1/2)\alpha_{\mathrm{int}}\phi\,, \tag{1}$$

$$\frac{\partial N}{\partial \tau} = \frac{I}{qV} - \frac{N}{\tau_c} - \frac{a}{A_m h\nu}(N - N_0)(1 - \epsilon|\phi|^2)|\phi|^2 . \tag{2}$$

In these equations ϕ is the electric-field envelope (which is normalized so that the optical power $P = |\phi|^2$), N is the carrier density, N_0 is the transparent carrier density, Γ is the confinement factor, a is the gain coefficient, β is the linewidth-broadening factor, $\overline{\beta}$ relates to the refractive-index change that is due to the nonlinear gain, ϵ is the gain saturation coefficient, α_{int} is the internal loss coefficient, I is the injection current, q is the charge of a carrier, V is the active volume, τ_c is the carrier lifetime, A_m is the mode cross section, and $h\nu$ is the photon energy. Two sources of NDFWM are included in Eqs. (1) and (2). One is the carrier-density modulation and is effective for beat frequencies as high as $\sim 1/\tau_c$. Typically $\tau_c = 0.2$–0.3 ns for the SLA. The other source originates from the intraband relaxation process occurring on a much shorter time scale, i.e., $\tau_i \cong 0.3$ ps. A complete treatment of this process should use the density matrix approach.[5] For simplicity, in Eqs. (1) and (2) we include the first-order effect of the nonlinear compression of the optical gain by a factor $\epsilon|\phi|^2$, which is responsible for spectral hole burning and highly NDFWM.[4–6] This model is valid when the beat frequency is much less than $1/\tau_i$ and the pulse width is much larger than τ_i. To show the phase-conjugate wave generated from the carrier-density and the nonlinear gain effects, we may decompose the field envelope and the carrier density as

$$\phi = \phi_p + \phi_s \exp(i\Omega\tau) + \phi_c \exp(-i\Omega\tau)\,, \tag{3a}$$

$$N = \overline{N} + \Delta N \exp(i\Omega\tau) + \Delta N^* \exp(-i\Omega\tau)\,, \tag{3b}$$

where ϕ_p is the pump wave with frequency ω_0, ϕ_s and ϕ_c are the signal wave and the conjugate wave with frequencies $\omega_0 - \Omega$ and $\omega_0 + \Omega$, respectively, $\overline{N}$ is the slowly varying carrier density, and ΔN is the fast-varying carrier density, which responds to the angular beat frequency Ω. Substituting Eqs. (3) into Eqs. (1) and (2) and neglecting the higher-order terms, we have the following equation for the conjugate wave:

$$\begin{aligned}\frac{\partial \phi_c}{\partial z} = {} & \frac{1}{2}\Gamma a(1 - i\beta)(\overline{N} - N_0)\phi_c - \frac{1}{2}\alpha_{\mathrm{int}}\phi_c \\ & - \frac{1}{2}\Gamma a(1 - i\beta)(\overline{N} - N_0)\gamma \\ & \times \frac{|\phi_p|^2\phi_c + {\phi_p}^2\phi_s^*}{1 + \gamma(|\phi_p|^2 + |\phi_s|^2 + |\phi_c|^2) - i\Omega\tau_c} \\ & - \frac{1}{2}\Gamma a(1 - i\overline{\beta})(\overline{N} - N_0) \\ & \times \epsilon[(|\phi_c|^2 + 2|\phi_s|^2 + 2|\phi_p|^2)\phi_c + {\phi_p}^2\phi_s^*]\,,\end{aligned} \tag{4}$$

where $\gamma = a\tau_c/A_m h\nu$. On the right-hand side of Eq. (4) the first term shows the gain from the

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carrier density, the third and fourth terms show the effects from the carrier-density modulation and nonlinear gain effect, respectively, and the terms with ${\phi_p}^2\phi_s^*$ are the sources of the OPC. From Eq. (4) we see that, when the beat frequency is high, the OPC from the carrier-density modulation is reduced and the nonlinear gain effect is the dominant source for OPC. We take the following typical numerical parameters for the SLA: $\Gamma = 0.4$, $a = 2.5 \times 10^{-16}$ cm^2, $N_0 = 1 \times 10^{18}$ cm^{-3}, $\alpha_{\text{int}} = 40$ cm^{-1}, $\beta = 6$, $\tau_c = 0.25$ ns, amplifier length $L = 250$ μm, active-region width $w = 2$ μm, active-region depth $d = 0.2$ μm, $V = Lwd$, and $A_m = wd/\Gamma$. For this amplifier structure, $\epsilon = 5.82$ W^{-1},[5] and because $|\overline{\beta}| \ll 1$,[6] we take $\overline{\beta} = 0$.

The signal pulse launched into the SLA is assumed to be a Gaussian pulse that has propagated in an 80-km-long standard fiber with a 0.22-dB loss and a 16-ps/(km nm) dispersion. The pulse also experiences self-phase modulation from the Kerr effect in the fiber, in which the Kerr coefficient is 3.2×10^{-20} m^2/W and the effective fiber cross section is 50 μm^2. The carrier wavelength $\lambda_s = 1551$ nm, and the pulse's initial field envelope is assumed to be $\phi_1 = \sqrt{P_1} \exp[-(t/\sigma_1)^2]$, where P_1 and σ_1 are its initial peak power and rms pulse width, respectively. We take $P_1 = 3$ mW and a short pulse width $\sigma_1 = 50$ ps to enhance the pulse broadening. At the end of the fiber the pulse broadens, and its rms pulse width becomes 78 ps. The pulse is then launched into the SLA with peak power P_2. The pump wave is a continuous wave with wavelength $\lambda_p = 1550$ nm, and the pump power in the SLA is P_p. The input field envelope of the SLA is taken as

$$\phi = \sqrt{P_p} + \phi_2 \exp(-i\Omega\tau), \tag{5}$$

where ϕ_2 is the input signal pulse. Before the pump wave and active medium interact with the signal pulse ($\tau = -\infty$), the carrier density is saturated by the pump wave. We take Eq. (5) and the saturation carrier density that can be obtained by setting $\partial N/\partial\tau = 0$ in Eq. (2) as initial conditions to solve Eqs. (1) and (2).

Figure 1 shows the power envelopes of the conjugate pulses of wavelength $\lambda_c = 1549$ nm at the output of the SLA with $I = 250$ mA and $P_p = 1$ mW for $P_2 = 0.1$, 0.5, and 1 mW. In the figure the power envelopes are normalized with respect to their peak powers P_{cp}, and the input signal pulse into the SLA is also shown for comparison. $P_{cp} = 0.0849$, 0.261, and 0.313 mW for $P_2 = 0.1$, 0.5, and 1 mW, respectively. One can see that, although P_{cp} increases with P_2, the pulse broadens and distorts asymmetrically as P_2 increases. The rms pulse widths of the output conjugate pulses are $\sigma_c = 79.7$, 85.8, and 93.0 ps for $P_2 = 0.1$, 0.5, and 1 mW, respectively. From Eq. (4) we can see that, because the gain is proportional to $(\overline{N} - N_0)$, the depletion of the slowly varying carrier density $\overline{N}$ by the signal pulse is responsible for the pulse-shape distortion. Figure 2 shows the carrier density N in the SLA for the case of $P_2 = 1$ mW shown in Fig. 1, in which the fast-varying carrier density ΔN responds to the beat frequency $\Omega/2\pi = 125$ GHz. One can see that the carrier density in the leading edge of the conjugate pulse is larger than the carrier density in the trailing edge. Therefore the leading edge of the conjugate pulse experiences more gain than the trailing edge, leading to asymmetrical distortion. Furthermore, the central part of the conjugate pulse experiences less gain than the other parts of the conjugate pulse, leading to pulse broadening. Because the depletion of $\overline{N}$ increases with the signal

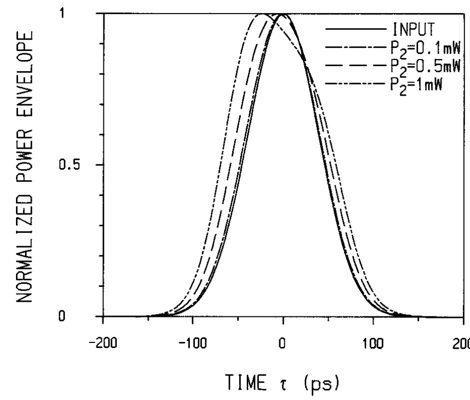

Fig. 1. Normalized power envelopes of the conjugate pulses at the output of the SLA for signal powers $P_2 = 0.1$, 0.5, and 1 mW. The input power envelope of the signal pulse into the SLA is also shown for comparison.

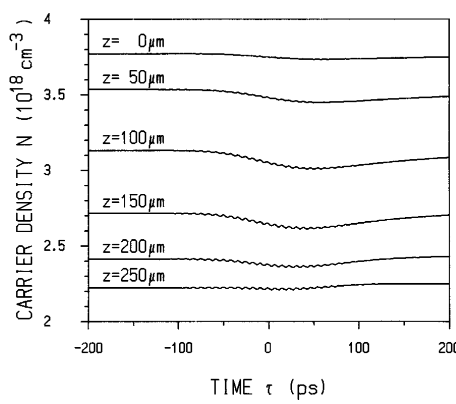

Fig. 2. Carrier density N in the SLA for the case of signal power $P_2 = 1$ mW shown in Fig. 1. The corresponding distance z is indicated for each curve.

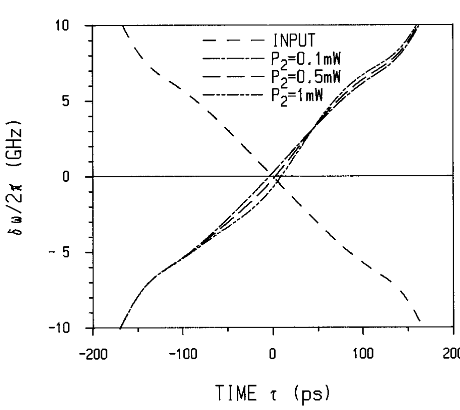

Fig. 3. Corresponding instantaneous frequencies $\delta\omega$ of the output conjugate pulses and the input signal pulse shown in Fig. 1.

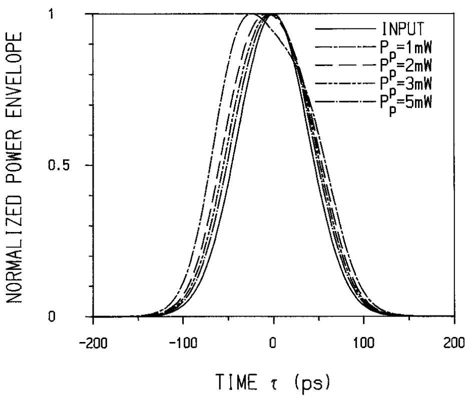

Fig. 4. Normalized power envelopes of the conjugate pulses at the output of the SLA for pump powers $P_p = 1, 2, 3$, and 5 mW. The signal power $P_2 = 1$ mW. The input power envelope of the signal pulse into the SLA is also shown.

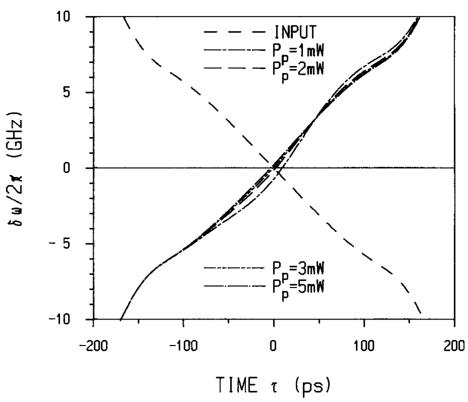

Fig. 5. Corresponding instantaneous frequencies $\delta\omega$ of the output conjugate pulses and the input signal pulse shown in Fig. 4.

power, the distortion of the conjugate pulse increases with the signal power. Note that the contribution of NDFWM from the carrier-density modulation is small in these cases. If we assume that $\epsilon = 0$, the output conjugate powers are reduced by approximately a factor of 10. As to the phase of the conjugate pulse, Fig. 3 shows the instantaneous frequencies $\delta\omega$ for the conjugate pulses shown in Fig. 1, in which $\delta\omega = -\partial\psi/\partial\tau$, where ψ is the phase of the conjugate pulse. For comparison Fig. 3 also shows the $\delta\omega$ of the input signal pulse, which is due to chromatic dispersion and self-phase modulation in the standard fiber. One can see that the $\delta\omega$ of the conjugate pulse is composed of inverted chirping of the input signal pulse plus some additional frequency chirping. The additional frequency chirping comes from the phase modulation by the slowly varying carrier density $\overline{N}$. Using the first term on the right-hand side of Eq. (4), we can write the additional frequency chirping as $\delta\omega_a(L, \tau) = (1/2)\beta\Gamma a \int_0^L \partial\overline{N}(z, \tau)/\partial\tau dz$. Since the pulse-shape distortion and additional frequency chirping come from the depletion of the carrier density, a higher injection current provides higher gain, but these two effects also increase.

To reduce the pulse-shape distortion and additional frequency chirping of the conjugate pulse, we may use higher pump powers to reduce the carrier-density depletion induced by the signal pulse. Figures 4 and 5 show the power envelopes and $\delta\omega$'s of the output conjugate pulses, respectively, for $P_2 = 1$ mW and several pump powers P_p. One can see that both the pulse-shape distortion and additional frequency chirping decrease as P_p increases. The rms pulse widths are $\sigma_c = 86.7$, 84.2, and 81.9 ps for $P_p = 2$, 3, and 5 mW, respectively. However, the output conjugate power does not necessarily increase with P_p. At higher pump powers, although more conjugate power may be generated through NDFWM, the gain from the carrier density is compressed by the pump power. Thus there exists an optimal pump power for the maximum output conjugate power. For the case when $I = 250$ mA the optimal pump powers are 0.6, 1.8, and 3.0 mW for $P_2 = 0.1$, 0.5, and 1 mW, respectively. The corresponding maximum powers $P_{cp} = 0.0877$, 0.280, and 0.422 mW for $P_2 = 0.1$, 0.5, and 1 mW, respectively.

In conclusion, the pulse-shape distortion and frequency chirping of a conjugate pulse that are due to the carrier-density depletion induced by the signal pulse in a SLA have been demonstrated. Both effects are enhanced as the signal power and the injection current increase. It is found that we can reduce these effects by increasing the pump power to reduce the carrier-density depletion induced by the signal pulse. As the pump power compresses the gain from the carrier density, there exists an optimal pump power for the maximum output conjugate power.

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