Spectral shift and distortion due to self-phase modulation of picosecond pulses in 1.5 μm optical amplifiers

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Picosecond pulses are observed to exhibit large frequency shifts (~ 50 GHz) and spectral distortion on propagation through semiconductor laser optical amplifiers. The spectral changes are shown to result from self-phase modulation occurring due to the carrier-induced index changes that invariably accompany gain saturation. An analytic model for pulse amplification is presented by including the self-phase modulation effects. Its predictions are in good agreement with the experimental results.

The picosecond amplification characteristics of semiconductor laser amplifiers have recently been reported in a number of experiments.[1-4] These studies have shown that semiconductor laser amplifiers can provide output peak powers in excess of 100 mW for pulse widths of 50 ps.[1] Amplification of 3–9 ps pulses has been demonstrated with no distortion in the pulse shape for input pulse energies of up to 52 fJ.[2] Pulse broadening and pulse compression can occur under some conditions depending on both the input peak power and the input pulse width.[3] The picosecond[4] and subpicosecond[5] gain-recovery characteristics have also been measured recently.

In all these studies, only the temporal characteristics of the input and the amplified output pulses have been considered. The spectral characteristics have been either ignored or masked by using spectrally broad light sources. In this letter we report the first investigation of the spectral characteristics of pulse amplification in semiconductor laser amplifiers. It will be shown that input pulses with widths in the 10–50 ps range, although remaining temporally undistorted, can be frequency shifted and spectrally distorted as a result of gain saturation in the amplifier. The experimental results are well explained by a theoretical model that includes index changes occurring as a result of carrier density variations in the gain saturation dynamics. The physical mechanism behind the spectral distortion is the self-phase modulation (SPM).

The experimental setup is shown in Fig. 1. The picosecond light pulses are generated in a mode-locked, external-cavity semiconductor laser. The laser has a grating external reflector for tuning and bandwidth control and operates at a pulse repetition rate of 1 GHz. The laser generates nearly transform-limited 8–50 ps wide pulses in the 1.47–1.55 μm spectral range. The time-bandwidth product is typically 0.5. To increase the pulse energy, the pulses are first amplified in a traveling-wave semiconductor laser amplifier, OAMP1 in Fig. 1. OAMP1 operates far from saturation so that the nonlinear effects are negligible. The output from OAMP1 is coupled into the second optical amplifier, OAMP2, via an optical isolator, a short section of a single-mode fiber, and bulk optics. The output from OAMP2 is split into two parts, one going to a scanning spectrometer with 0.5 Å resolution, and the other going to a streak camera for temporal measurements. Both amplifiers are of the traveling-wave type with facet reflectivities of less than 0.01% and have unsaturated chip gains of up to 30 dB.[6]

With the experimental setup of Fig. 1 the temporal and spectral gain characteristics of OAMP2 were investigated. When the amplifier operates well below saturation, no spectral or temporal distortion occurs, and the input and output spectra and pulse shapes are nearly identical. The spectrum and the pulse shape for the unsaturated case are shown in Figs. 2(a) and 3(a) for an input pulse energy of 0.18 pJ (coupled into OAMP2) and a drive current of 30 mA, giving the unsaturated gain of 11 dB. The output pulse width (full width at half maximum, FWHM) of 15.6 ps and the spectral FWHM of 2.5 Å are identical to those of the input pulse. When the drive current of OAMP2 is increased to 130 mA, giving an unsaturated gain of approximately 30 dB, the output spectrum and the pulse shape of Figs. 2(b) and 3(b) are obtained. As seen in Fig. 2, the peak output wavelength has shifted 3.1 Å (42 GHz) towards longer wavelengths. In addition, a secondary peak appears 4 Å below the main peak, and the main peak is considerably broadened. The pulse shape shown in Fig. 3(b), however, is only slightly distorted with a somewhat increased tail at the trailing edge of the pulse. The lower baseline intensity near the trailing edge of the pulse in Fig. 3(b) is caused by reduced spontaneous emission from OAMP2 after gain saturation from the pulse. Results similar to those shown in Figs. 2 and 3 were obtained for pulse widths ranging from 9 to 40 ps. The observed spectral changes are not critically dependent on the input pulse width.

The spectral distortion can be understood in terms of SPM of the picosecond pulses in the optical amplifier. The

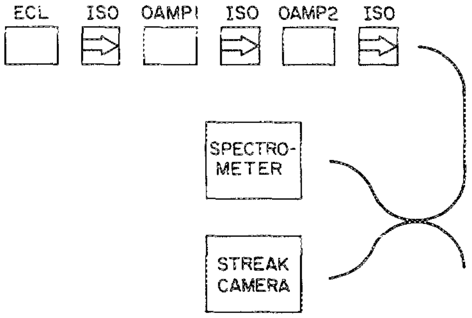

FIG. 1. Experimental setup. ECL = mode-locked external cavity semiconductor laser, ISO = optical isolater, OAMP = optical amplifier.

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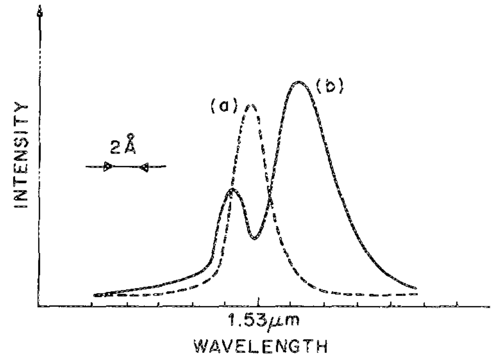

FIG. 2. Output pulse spectrum for OAMP2 gain of (a) 11 dB and (b) 30 dB.

changes in the carrier density occurring as a result of gain saturation affect not only the amplifier gain but also the refractive index. The resulting time-dependent index variations lead to SPM, a phenomenon that is known to produce spectral changes when ultrashort pulses propagate in a nonlinear medium.[7] In the following, we present a simple analytic model that is capable of explaining our experimental results.

The electric field inside a traveling-wave amplifier can be written as

$$E(x,y,z,t) = \tfrac{1}{2}\{F(x,y)A(z,t)\exp[i(k_0 z - \omega_0 t)] + \text{c.c.}\}, \tag{1}$$

where ω_0 is the optical frequency, $k_0 = \bar{n}\omega_0/c$, $\bar{n}$ is the effective mode index, $F(x,y)$ is the transverse distribution of the fundamental waveguide mode, and $A(z,t)$ is the slowly varying envelope associated with the optical pulse. The evolution of $A(z,t)$ inside the amplifier is governed by

$$\frac{\partial A}{\partial z} + \frac{1}{v_g}\frac{\partial A}{\partial t} = \frac{1}{2}(1 - i\alpha)g(N)A, \tag{2}$$

where v_g is the group velocity, $g(N)$ is the optical gain, and α is the linewidth enhancement factor introduced to account for the carrier-induced index changes. The parameter α plays an important role in determining the performance of semiconductor lasers.[8] It also affects the characteristics of semiconductor laser amplifiers through four-wave mixing.[9] Its typical values for InGaAsP lasers and amplifiers are in the range 4–6 depending on the operating wavelength.

The optical gain $g(N)$ varies approximately linearly with the carrier density N and can be written in the form[8]

$$g(N) = \Gamma a(N - N_0), \tag{3}$$

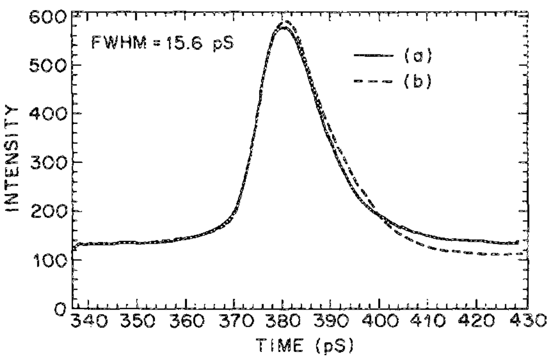

FIG. 3. Output pulse shape for OAMP2 gain of (a) 11 dB and (b) 30 dB.

where Γ is the confinement factor, a is the gain coefficient, and N_0 is the carrier density required for transparency. The carrier density N satisfies the rate equation

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_c} - \frac{g(N)}{\hbar\omega_0}|A|^2, \tag{4}$$

where I is the injection current, q is the electron charge, V is the cavity volume, and τ_c is the spontaneous carrier lifetime. By using Eqs. (3) and (4), the gain dynamics are governed by

$$\frac{\partial g}{\partial t} = -\frac{g - g_0}{\tau_c} - \frac{g|A|^2}{E_{\text{sat}}}, \tag{5}$$

where $E_{\text{sat}} = \hbar\omega_0\sigma/a$ is the saturation energy, σ is the mode cross-section area, and g_0 is the small-signal gain.

Equations (2) and (5) govern the dynamics of the amplification process and are applicable for pulses of arbitrary durations. They can be solved in a closed form if the pulse width $\tau_p \ll \tau_c$ so that carrier injection and carrier recombination can be ignored during the passage of the pulse.[10] The result is

$$A_{\text{out}}(\tau) = A_{\text{in}}(\tau)\exp[\tfrac{1}{2}(1 - i\alpha)h(\tau)], \tag{6}$$

where $\tau = t - z/v_g$, the integrated gain $h(\tau)$ is given by

$$h(\tau) = \int_0^L g(z,\tau)dz = -\ln\left[1 - \left(1 - \frac{1}{G_0}\right)\exp\left(-\frac{U_{\text{in}}(\tau)}{E_{\text{sat}}}\right)\right], \tag{7}$$

$G_0 = \exp(g_0 L)$ is the unsaturated single-pass amplifier gain and

$$U_{\text{in}}(\tau) = \int_{-\infty}^{\tau} |A_{\text{in}}(\tau')|^2 d\tau'. \tag{8}$$

The spectrum of the output pulse is obtained by taking the Fourier transform of Eq. (6).

Equations (6)–(8) can be used to obtain the shape and the spectrum of the amplified pulses if the input pulse shape is specified. We apply them to the case of a Gaussian input pulse by taking

$$A_{\text{in}}(\tau) = \sqrt{P_{\text{in}}}\exp(-\tau^2/2\tau_0^2), \tag{9}$$

where P_{in} is the peak power and τ_0 is related to the FWHM

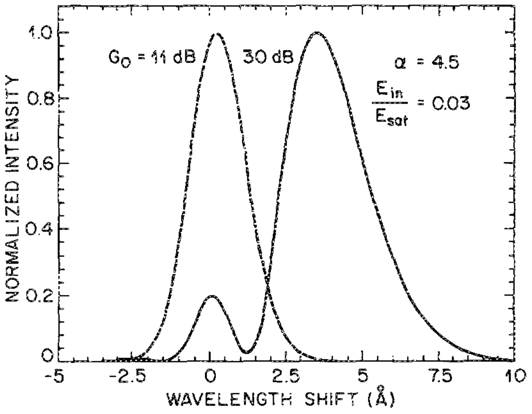

FIG. 4. Calculated pulse spectrum for the amplifier gain of 11 dB and 30 dB.

by $\tau_p \simeq 1.665\tau_0$. By using Eqs. (8) and (9), we obtain

$$U_{\text{in}}(\tau) = \tfrac{1}{2}E_{\text{in}}[1 + \text{erf}(\tau/\tau_0)], \tag{10}$$

where E_{in} is the input pulse energy. Figure 4 shows the calculated spectra for output pulses using parameter values corresponding to the experimental spectra of Fig. 2. The saturation energy for the amplifier was estimated to be 6 pJ, resulting in $E_{\text{in}}/E_{\text{sat}} = 0.03$ for the input pulse energy of 0.18 pJ. The parameter α can be adjusted to fit the data. The spectra shown in Fig. 4 for $\alpha = 4.5$ should be compared with the experimental results of Fig. 2. The theory predicts a two-peak spectrum for the 30 dB gain, as also observed experimentally. The peak separation of 3.6 Å is in agreement with the measured value of 4 Å. More important, the wavelength of the main peak has shifted by 3.2 Å from the spectral peak corresponding to 11 dB gain, again in agreement with measured value of 3.1 Å. The amplitude of the secondary peak is smaller than the measured amplitude. This discrepancy can be attributed to the details of the pulse shape. The input pulse is not a perfect Gaussian, as assumed in obtaining Fig. 4. The overall agreement is nonetheless remarkable. The calculated pulse shapes also agree well with those shown in Fig. 3.

In conclusion, amplification of picosecond optical pulses in semiconductor laser amplifiers can be accompanied by considerable spectral distortion even when the pulse shape remains nearly unchanged. The physical mechanism behind the spectral changes is SPM that occurs when the amplifier is saturated. In general, the pulse spectrum is shifted toward red and is accompanied by one or more side peaks on the blue side. This type of distortion would affect the pulse shape considerably when the pulses are propagated through an optical fiber and could affect the performance of high-speed optical communication systems employing in-line amplifiers.

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