Amplification and compression of weak picosecond optical pulses by using semiconductor-laser amplifiers

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A novel pulse-compression scheme is proposed and demonstrated for compressing weak picosecond pulses having energies as small as 0.1 pJ. A semiconductor-laser amplifier is shown to impose a nearly linear frequency chirp on the pulse as a result of self-phase modulation occurring because of gain-saturation-induced index changes. The amplified chirped pulse can be compressed by passing it through a dispersive delay line. The theory shows that, depending on the operating conditions, the pulse width can be reduced by a factor of ~2–4 and the peak power can be enhanced by a factor of ~10–100. The preliminary experimental results are in agreement with theory.

The use of optical fibers for pulse compression has become widespread in recent years.[1,2] When an intense optical pulse propagates down a fiber, the nonlinear phenomenon of self-phase modulation (SPM) imposes a nearly linear frequency chirp across the pulse. The chirped pulse can be compressed by passing it through a dispersive delay line such as a grating pair[3] or a dispersive medium having anomalous group-velocity dispersion (GVD). Because of a relatively weak fiber nonlinearity such pulse-compression techniques work only when the input pulses have relatively high peak powers with pulse energies exceeding 10–100 pJ.

In this Letter we propose and demonstrate a novel pulse-compression scheme that can be used to compress weak picosecond pulses having energies as small as 0.1 pJ. The basic idea is to amplify such pulses in a semiconductor-laser amplifier. The gain-saturation-induced temporal variations in the carrier density of the amplifier lead to SPM as the pulse propagates through the amplifier.[4] The amplified pulse has a nearly linear chirp over the central part of the pulse and can be compressed by using a dispersive delay line. Even though the compression factor is generally not very large (~2–4), the compressed pulse can have its peak power enhanced by a factor of ~10–100 as a result of amplification inside the semiconductor laser amplifier.

To understand the origin of pulse compression, we first consider the theory of pulse propagation in a traveling-wave semiconductor-laser amplifier.[4] In the slowly varying envelope approximation the pulse evolution is governed by

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

where A is the amplitude of the pulse envelope, v_g is the group velocity, and the gain varies approximately linearly with the carrier density N, i.e.,

$$g(N) = \Gamma a(N - N_0). \qquad (2)$$

Here a is the gain coefficient and N_0 is the carrier density required for transparency.[5] The confinement factor Γ accounts for the spread of the optical mode outside the active region of the amplifier. The parameter α in Eq. (1) is introduced to take into account the refractive-index changes that accompany the carrier-density variations occurring as a result of gain saturation. It is sometimes referred to in the literature on semiconductor lasers as the linewidth enhancement factor.[5–7] It will be seen that the parameter α is responsible for SPM and the subsequent compression of optical pulses. Its typical values for InGaAsP amplifiers are in the range of 4–6, depending on the operating wavelength.

The time dependence of the optical gain is governed by the carrier-density rate equation

$$\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_c} - \frac{g|A|^2}{\hbar\omega_0}, \qquad (3)$$

where I is the injection current, V is the active volume, and τ_c is the spontaneous carrier lifetime. By using Eq. (2) in Eq. (3) the gain satisfies

$$\frac{\partial g}{\partial t} = \frac{g_0 - g}{\tau_c} - \frac{g|A|^2}{E_{sat}}, \qquad (4)$$

where $g_0 = \Gamma a(I\tau_c/qV - N_0)$ is the small-signal gain of the amplifier and $E_{sat} = \hbar\omega_0\sigma/a$ is the saturation energy. Here $\sigma = V/\Gamma L$ is the cross-section area of the optical mode and L is the amplifier length. Typically $\sigma \sim 1\ \mu m^2$ and $a = 2$–$3 \times 10^{-16}\ cm^2$, resulting in $E_{sat} \sim$ 5–6 pJ.

Equations (1) and (4) can be solved in a closed form if the pulse width $\tau_p \ll \tau_c$.[8–10] Typically $\tau_c = 0.2$–0.3 nsec, and the above condition is satisfied for pulse widths $\lesssim$20–40 psec. For such short pulses the term containing τ_c in Eq. (4) can be ignored, as stimulated recombination dominates the gain dynamics. The result is

$$A_{out}(\tau) = A_{in}(\tau)\exp[\tfrac{1}{2}(1 - i\alpha)h(\tau)], \qquad (5)$$

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where $\tau = t - z/v_g$ and the integrated gain $h(\tau)$ is given by[11]

$$h(\tau) = \int_0^L g(z, \tau)\mathrm{d}z$$

$$= -\ln\left\{1 - \left(1 - \frac{1}{G_0}\right)\exp\left[-\frac{U_{\mathrm{in}}(\tau)}{E_{\mathrm{sat}}}\right]\right\}. \quad (6)$$

In Eq. (6), $G_0 = \exp(g_0 L)$ is the unsaturated amplifier gain and $U_{\mathrm{in}}(\tau)$ is the partial pulse energy, defined by

$$U_{\mathrm{in}}(\tau) = \int_{-\infty}^{\tau} |A_{\mathrm{in}}(\tau')|^2 \mathrm{d}\tau'. \quad (7)$$

The SPM-induced phase shift from Eq. (5) is

$$\phi_{\mathrm{SPM}}(\tau) = -\frac{\alpha}{2} h(\tau). \quad (8)$$

The frequency chirp imposed on the pulse is obtained by differentiating Eq. (8) and is given by

$$\Delta\nu = -\frac{1}{2\pi}\frac{\partial\phi_{\mathrm{SPM}}}{\partial\tau}$$

$$= -\frac{\alpha(G_0 - 1)}{4\pi G_0}\frac{P_{\mathrm{out}}(\tau)}{E_{\mathrm{sat}}}\exp\left[-\frac{U_{\mathrm{in}}(\tau)}{E_{\mathrm{sat}}}\right], \quad (9)$$

where the output power is obtained from

$$P_{\mathrm{out}}(\tau) = |A_{\mathrm{out}}(\tau)|^2 = |A_{\mathrm{in}}(\tau)|^2 \exp[h(\tau)]. \quad (10)$$

Figure 1 shows the frequency chirp across the amplified pulse for the case of an unchirped Gaussian input pulse with the amplitude

$$A_{\mathrm{in}}(\tau) = \left(\frac{E_{\mathrm{in}}}{\tau_0\sqrt{\pi}}\right)^{1/2} \exp\left(-\frac{\tau^2}{2\tau_0^2}\right), \quad (11)$$

where E_{in} is the input pulse energy and τ_0 is related to the full width at half-maximum (FWHM) by $\tau_p \simeq 1.665\,\tau_0$. The unsaturated amplifier gain $G_0 = 30$ dB, $\alpha = 5$, and $E_{\mathrm{in}}/E_{\mathrm{sat}}$ is varied over the range 0.01 to 0.2.

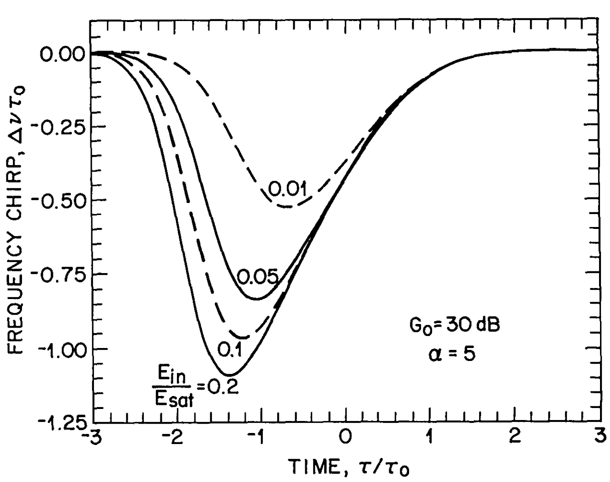

Fig. 1. Frequency-chirp profiles of the amplified pulse for several input pulse energies when a Gaussian pulse is amplified in a semiconductor-laser amplifier with an unsaturated gain of 30 dB.

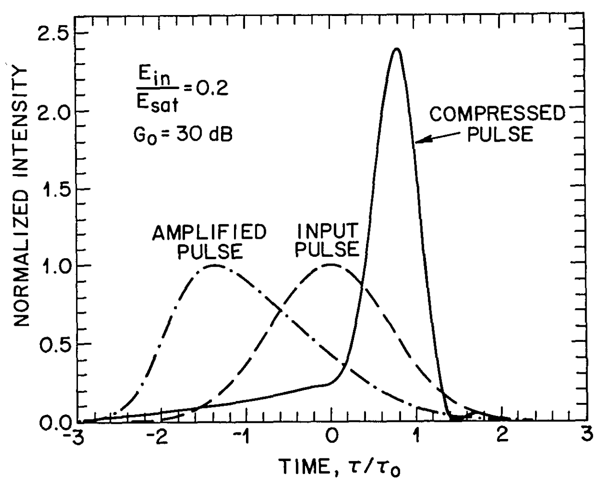

Fig. 2. Compressed pulse when the amplified pulse is passed through a dispersive delay line such that $L_C/L_D = 0.3$. The dashed curve shows the input pulse, and the dotted–dashed curve shows the amplified pulse before compression.

The instantaneous frequency is downshifted from the incident frequency $\nu_0 = \omega_0/2\pi$ across the entire pulse ($\Delta\nu < 0$). The chirp profile is asymmetric in such a way that the chirp increases almost linearly over the central part ($|\tau| \lesssim \tau_0$) of the pulse. Such a linear chirp implies that the amplified pulse can be compressed by passing it through a dispersive delay line with anomalous GVD. The amplitude of the compressed pulse is obtained by using

$$A_{\mathrm{comp}}(\tau) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{A}_{\mathrm{out}}(\omega)\exp\left(\frac{i}{2}\beta_2\omega^2 L_C - i\omega\tau\right)\mathrm{d}\omega, \quad (12)$$

where $\tilde{A}_{\mathrm{out}}(\omega)$ is the Fourier transform of Eq. (5), β_2 is the GVD coefficient, and L_C is the length of the compressor. It is useful to define the dispersion length by the relation $L_D = \tau_0^2/|\beta_2|$. An unchirped pulse would broaden by a factor of $\sqrt{2}$ when $L_C = L_D$. The chirped pulse, however, broadens or compresses depending on whether $\beta_2 > 0$ or $\beta_2 < 0$. In what follows we consider the case of anomalous GVD by setting $\beta_2 < 0$.

Figure 2 shows the compressed pulse when a Gaussian input pulse is amplified and subsequently compressed by using a dispersive delay line of length such that $L_C/L_D = 0.3$. The unsaturated amplifier gain $G_0 = 30$ dB, $\alpha = 5$, and $E_{\mathrm{in}}/E_{\mathrm{sat}} = 0.2$. The chirped pulsed at the amplifier output is also shown for comparison. The input pulse has been compressed by a factor of ~3 because of the SPM-induced chirp imposed on the pulse by the amplifier. The pulse has a broad pedestal on the leading side, but its energy is below 20% of the main pulse. The origin of the pedestal can be understood by noting that the chirp on the leading edge (see Fig. 1) is such that the energy contained in it disperses away with propagation. The pedestal can be removed by passing the pulse through an intensity discriminator.[12] The compression factor depends on several input parameters, such as the pulse energy, the pulse width, the amplifier gain, and the compressor length L_C. In general, maximum compression occurs for an optimum value of L_C/L_D. Typically, the com-

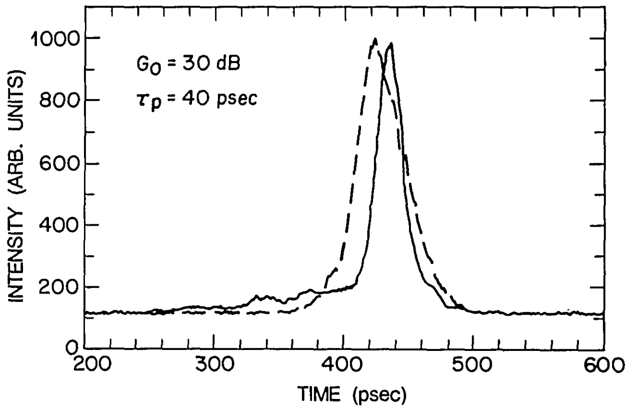

Fig. 3. Experimental traces of the pulse shape obtained by using a streak camera for the compressed pulse (solid curve) and the input pulse (dashed curve).

pression factor is in the range 2–4, depending on the input pulse parameters.

To demonstrate the feasibility of the proposed pulse-compression scheme we have performed an experiment in which 1.52-μm 40-psec (FWHM) input pulses were amplified and subsequently compressed by using a single-mode fiber as a dispersive delay line. The input pulses are obtained from a mode-locked, external-cavity semiconductor laser operating at a pulse-repetition rate of 1 GHz and tunable over the 1.47–1.55-μm spectral range. The laser generates nearly transform-limited pulses with a time–bandwidth product of ~0.5. The semiconductor-laser amplifier is a traveling-wave type with facet reflectivities of $<10^{-4}$. With a drive current of 110 mA, it provides an unsaturated gain of ~30 dB over a wide bandwidth (~5 THz) near 1.52 μm. The amplified pulse is coupled into an 18-km-long single-mode fiber having $\beta_2 \simeq -18$ psec^2/km at 1.52 μm. The pulse shape is monitored through a streak camera, while the pulse spectrum is measured by using a scanning spectrometer with 0.05-nm resolution.

Figure 3 shows the compressed pulse together with the input pulse for a 40-psec input pulse of energy $\simeq$0.1 pJ ($E_{in}/E_{sat} \simeq 0.02$). The theoretical pulse shapes are in good agreement with the measured ones for the experimental values of the parameters ($L_C/L_D \simeq 0.5$). The 23-psec FWHM of the compressed pulse corresponds to a compression factor of only 1.7. Its peak power is, however, enhanced by a factor of ~20. This enhancement results from the net gain after the coupling losses and the fiber losses are subtracted from the amplifier gain. The peak-power enhancement can be improved by reducing the coupling losses (~10 dB in our experiment). The fiber loss can also be reduced for shorter input pulses ($L_C \lesssim 1$ km for 10-psec pulses). The important point is that the proposed compression scheme can be used for input pulse energies as low as 0.1 pJ. Such weak picosecond pulses are difficult to compress by other means.

In conclusion, we have proposed and demonstrated a new pulse-compression scheme for compressing weak picosecond pulses by amplifying them in a semiconductor-laser amplifier and then passing them through a dispersive delay line. The amplifier plays a dual role as it imposes a nearly linear chirp on the pulse together with amplifying the pulse. Depending on the input pulse energy and the amplifier gain, the pulse width can be reduced by a factor of 2–4, and the peak power can be enhanced by a factor exceeding 10–100. For wavelengths >1.3 μm, a single-mode fiber can act as a dispersive delay line and compress the pulse if its length is suitably optimized. In the visible and the near-infrared regions, a grating pair may be used for this purpose.[3] The applicability of the proposed scheme rests on whether a suitable semiconductor-laser amplifier is available in the wavelength region of interest. In the wavelength region near 1.5 μm InGaAsP amplifiers can be used to compress and amplify the pulses emitted by mode-locked semiconductor lasers. The GaAs amplifiers may be useful in the near-infrared region extending from 0.8 to 0.9 μm. Recent advances in the visible-semiconductor-laser technology may make this method suitable even for the visible region.

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