Amplification and compression of ultrashort fundamental solitons in an erbium-doped nonlinear amplifying fiber loop mirror

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A nonlinear amplifying loop mirror constructed from erbium-doped fiber is proposed for simultaneous amplification and compression of ultrashort fundamental solitons. Numerical simulations show that, unlike conventional erbium-doped fiber amplifiers in which nonlinear effects lead to serious degradation of pulse quality, the proposed device performs efficient high-quality amplification and compression of ultrashort fundamental solitons while it almost completely preserves the soliton nature of the input pulses. Moreover, the performance of the device is insensitive to small variations in the loop length and in the power-splitting ratio of the coupler. © 2003 Optical Society of America

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Ultrashort pulse amplification finds applications in many fields, such as ultrafast spectroscopy, optical signal processing, and soliton-based communication systems, because of the relatively low output power levels of commonly used short-pulse sources such as mode-locked semiconductor and fiber lasers. Erbium-doped fiber amplifiers (EDFAs) are ideal for pulse amplification owing to their broad bandwidths (~50 nm), high gains (approximately 40–50 dB), and high pulse-saturation energies (~1 μJ). However, distortionless amplification of ultrashort soliton pulses in EDFAs is difficult if fiber nonlinearities such as self-phase modulation and Raman self-scattering (RSS) are large.[1–4] These nonlinear effects lead to undesirable pulse shaping and serious degradation of the pulse quality. Although adiabatic amplification (small gain) gives high-quality pulses, the resulting energy gains are small and the amplifier length must increase exponentially with input pulse width to satisfy the adiabatic condition. This difficulty can be overcome by use of the chirped pulse amplification technique[5,6] in which first an input pulse is stretched by a dispersive delay line to ensure linear amplification and then the stretched and amplified pulse is recompressed through another delay line that has the opposite sign of dispersion. Because the nonlinearities in the amplifier are suppressed, efficient and distortionless pulse amplification can be achieved. However, the chirped pulse amplification technique does not compress the pulses because the amplifier nonlinearities are suppressed.

In this Letter we demonstrate that an erbium-doped nonlinear amplifying fiber loop mirror (ED-NALM) can efficiently amplify and compress ultrashort fundamental solitons and that the amplified pulses are extremely similar to solitons. Nonlinear optical loop mirrors (NOLMs) have been widely used for pulse compression[7,8] and pulse-pedestal suppression,[9] but NOLMs do not provide amplification because they are passive devices. To obtain high-quality pulse amplification in a NOLM, one can insert a lump amplifier at one end of the loop.[10,11] In the research reported here we place a distributed gain instead of a lump gain in the loop. In that described in Ref. 10 group-velocity dispersion was suppressed by use of a low-dispersion fiber loop to achieve high-quality amplification; as a result, pulse compression was inefficient. In the present design we utilize the interplay of group-velocity dispersion and self-phase modulation to compress the input solitons efficiently. The proposed scheme also differs from that in Ref. 11 in that here no adiabatic condition is required, which not only permits more-efficient pulse amplification and compression but also allows one to amplify long pulses with short loop lengths.

Ultrashort pulse amplification in an erbium-doped fiber can be described by[3,12]

$$i\,\frac{\partial u}{\partial \xi} + \frac{1}{2}(1 - id)\frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = \frac{i}{2}\,\mu u + i\delta\,\frac{\partial^3 u}{\partial \tau^3} + \tau_R u\,\frac{\partial |u|^2}{\partial \tau}\,, \qquad (1)$$

where ξ, τ, and $u(\xi, \tau)$, respectively, denote the propagation distance, time, and pulse amplitude normalized to input soliton parameters. The parameters μ, d, τ_R, and δ account for, respectively, the effects of gain, gain dispersion, RSS, and third-order dispersion. In real parameters,

$$\xi = \frac{z}{L_D} = \frac{z|\beta_2|}{{T_0}^2}\,, \qquad \tau = \frac{t - z/v_g}{T_0}\,,$$

$$d = g_0 L_D\,\frac{{T_2}^2}{{T_0}^2}\,, \qquad (2)$$

$$\mu = (g_0 - \alpha)L_D\,, \qquad \delta = \frac{\beta_3}{6|\beta_2|T_0}\,,$$

$$\tau_R = \frac{T_R}{T_0}\,, \qquad (3)$$

where T_0 is the half-width (at $1/e$-intensity point) of the input pulse, v_g is the group velocity, β_2 is the group-velocity dispersion coefficient, β_3 is the third-order dispersion coefficient, T_R is the Raman resonant time constant, α is the fiber loss, T_2 is the dipole relaxation time, g_0 is the unsaturated gain, and $L_D = {T_0}^2/|\beta_2|$ is the dispersion length. We do not include self-steepening and two-photon absorption effects because they are of much smaller significance than the other effects. We also neglect gain saturation because it depends on the repetition rate of an input pulse train. As we demonstrate below, the gain saturation of a single input pulse is negligible because the saturation energy of most amplifiers is much larger than that of a single pulse used in practice.

Before we investigate pulse amplification in an ED-NALM, we study pulse amplification in a conventional EDFA. We solve Eq. (1) numerically, using an input fundamental soliton $u(0, \tau) = \text{sech}(\tau)$ and the split-step Fourier method. We choose $T_0 = 0.4$ ps, $\beta_2 = -10$ ps^2/km, $\beta_3 = 0.1$ps^3/km, $T_R = 3$ fs, and $T_2 = 80$ fs, and we assume that the EDFA has a 10-dB gain per dispersion length L_D. From Eqs. (2) and (3) we have $\mu \approx 2.3$, $d \approx 0.092$, $\delta \approx 0.0042$, and $\tau_R = 0.0075$. Figures 1(a) and 1(b) show the evolution of the pulse shape and of the spectrum, respectively, over a distance $L \approx 1.7 L_D$, where the intensities of the pulse shape and of the spectrum are normalized to the peak intensities of the shape and the spectrum, respectively, of the input pulse. At $L \approx L_D$ ($\xi \approx 1$), the peak intensity is amplified by a factor of 53 with a compression factor of 8. The quality of the compressed pulse, however, is poor because nearly 22% of the pulse energy is contained in the pedestal. Beyond $\xi = 1$ the pedestal increases and a new pulse begins to form. The spectrum at $\xi = 1$ is asymmetric because of RSS and has a twofold structure, indicating that the pulse is considerably chirped.

The results are quite different if the same soliton is injected into an ED-NALM. The structure of the ED-NALM is identical to that of the NOLM,[13] except that the loop is constructed from an erbium-doped fiber with the same parameters μ, d, δ, and τ_R as those used for Fig. 1. The coupler has a power-splitting ratio of $r = 0.55$. Figures 2(a) and 2(b) show the transmitted pulse shapes at an optimal loop length ($L_{\text{opt}} \approx 1.33 L_D$) on linear and logarithmic scales, respectively. Optimal loop length L_{opt} is the loop length at which the transmitted pulse has a negligible pedestal and the peak intensity of the transmitted pulse reaches a maximum. At the optimum loop length, the transmitted pulse shape is extremely similar to a hyperbolic secant, save for a small asymmetry caused by RSS. The compression factor is 6.2, and the peak intensity is amplified by a factor of 59. Compared with the pulse obtained at maximum compression by use of an EDFA ($\xi = 1$ in Fig. 1), the peak intensity and energy contained in the pulse obtained with the ED-NALM are larger, whereas the compression factor is somewhat smaller because we have chosen a longer loop length to maximize the intensity of the transmitted pulse. Figures 2(c) and 2(d) show the spectrum and the frequency chirp, respectively, of the output pulse. We see that the spectrum's shape is nearly a hyperbolic secant, save for a small asymmetry in the central region caused by RSS. The chirp across the pulse is very small. The time–bandwidth product is 0.298, which is close to 0.315, the transform-limited value of a hyperbolic-secant pulse. From the peak intensity and width, the transmitted pulse is similar to a soliton with a soliton order of 1.24.

Pedestal suppression and soliton pulse formation result from the switching characteristics of the ED-NALM. Because the coupler is asymmetric, the two counterpropagating pulses are amplified differently, and they acquire different phase shifts when they recombine at the coupler. At the optimum loop length, the switching condition is satisfied for the

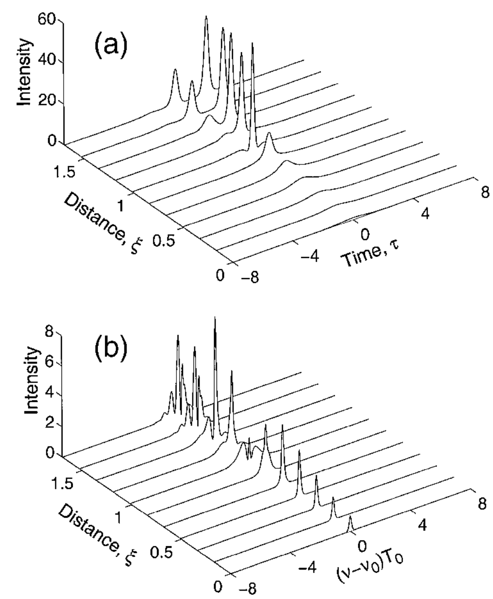

Fig. 1. (a) Temporal and (b) spectral evolution of an input fundamental soliton in an EDFA with 10-dB gain per dispersion length. The other parameters are $d = 0.092$, $\tau_R = 0.0075$, and $\delta = 0.0042$.

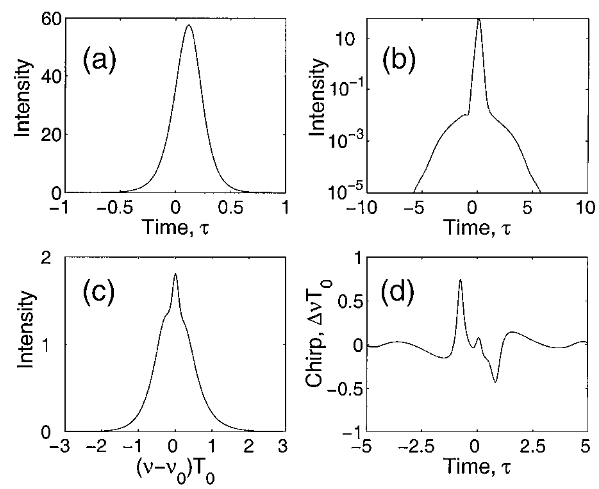

Fig. 2. Temporal shapes of the transmitted pulse on (a) linear and (b) logarithmic scales. (c) Spectrum and (d) frequency chirp of the transmitted pulse.

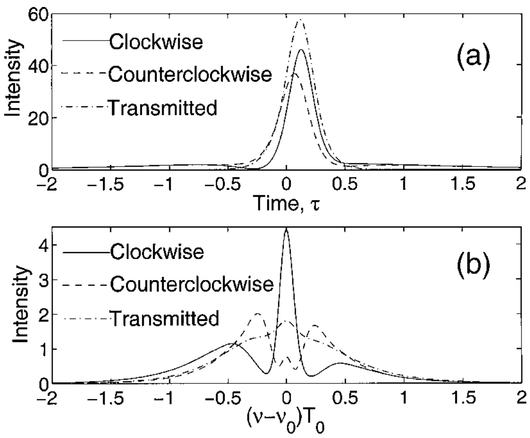

Fig. 3. (a) Temporal shapes and (b) spectra of the clockwise and the counterclockwise traveling pulses before recombination. The transmitted pulse is shown for comparison.

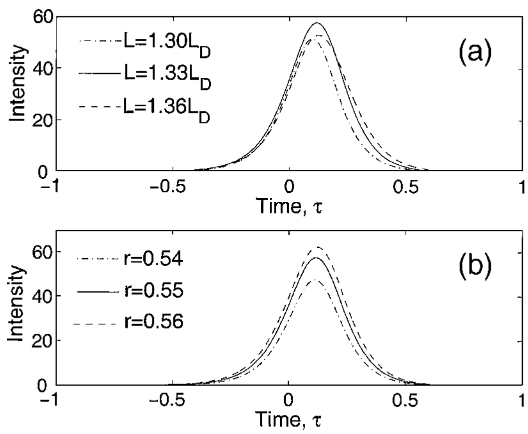

Fig. 4. Transmitted pulse shapes at (a) various loop lengths and (b) various coupler power-splitting ratios.

central peak but not for the rest of the pulse; thus the transmitted pulse is pedestal-free. Figure 3(a) shows the clockwise and counterclockwise pulse shapes after they travel around the loop but before they recombine at the coupler under conditions identical to those of Fig. 2. The shape of the transmitted pulse is given by the dashed–dotted curve. Figure 3(b) shows the spectra that correspond to Fig. 3(a). We see that, although the shapes and spectra of both the clockwise and the counterclockwise pulses deviate significantly from a hyperbolic-secant shape, the transmitted pulse and its spectrum are close to hyperbolic secants.

To study the robustness of the proposed scheme to variations in loop parameters, we compare the transmitted pulses in Fig. 4(a) at loop lengths of $L = 1.30L_D$, $1.33L_D$, $1.36L_D$. The corresponding loop lengths in real units are 20.80, 21.28, and 21.76 m. In all cases the parameters are identical to those used for Fig. 2, except for the loop length. Figure 4(b) compares the results at coupler power-splitting ratios $r = 0.54, 0.55, 0.56$. All other parameters are identical to those used for Fig. 2. We see that, unlike for conventional NOLMs, the performance of the ED-NALMs is fairly insensitive to variations in L and r. The reason is that for pulse amplification in an erbium-doped fiber the combined action of gain and gain dispersion tends to stabilize the width and the peak intensity of the pulse.[12] So, when the counterpropagating pulses are amplified to some extent, their widths and peak intensities change only slowly with propagation distance, leading to robustness of the device's performance to small variations in the parameters.

In conclusion, a nonlinear amplifying loop mirror constructed from erbium-doped fiber is proposed for simultaneous amplification and compression of ultrashort solitons. Numerical simulations show that, in contrast to a conventional EDFA in which nonlinear effects lead to serious degradation of pulse quality, the proposed device performs high-quality amplification and compression such that the amplified pulse retains its soliton nature almost completely. Although coherent effects[4]—which are neglected in the numerical model—may have an effect when input pulse width T_0 is comparable to T_2, we believe that coherent effects will not drastically change our main conclusions because they have similar influence on the counterpropagating pulses in the loop and should not drastically affect the switching characteristics of the device.

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