Decay of femtosecond pulses during amplification in single-mode optical fibers doped with Er^{3+} ions

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The decay of femtosecond pulses during amplification in single-mode optical fibers doped with Er^{3+} ions has been observed for the first time. The Stokes component of the split pulse is a soliton.

Optical fibers doped with ions of rare-earth elements on "active optical fibers" combine the properties of a guiding medium and of a laser active element and have accordingly become the subject of extensive research in recent years.[1] Among active optical fibers there is particular interest in those doped with erbium ions, whose broad luminescence band ($\sim 200\ \text{cm}^{-1}$) near 1.54 μm makes it possible to not only develop sources of laser light which operate in the region of the minimum loss and a negative dispersion of quartz optical fibers but also to study the amplification of nonlinear pulses in extended laser active media.

There is accordingly particular interest in the amplification of femtosecond stimulated Raman-scattering solitons with lengths comparable in magnitude to the transverse relaxation time of the ${}^4I_{13/2} - {}^4I_{15/2}$ lasing transition of Er^{3+}.

Figure 1 is a simplified diagram of the experimental apparatus. The stimulated Raman-scattering solitons are generated by a system consisting of a Q-switched, mode-locked Nd:YAG laser and a single-mode optical fiber 35 m long with a zero chromatic dispersion at the wavelength[2] $\lambda_0 = 1.32\ \mu$m. The simulated-Raman-scattering solitons which are formed, with a length of 80 fs, in the region 1.54 μm are coupled into the active fiber, with an erbium ion concentration of 1000 ppm. The cutoff wavelength for the first higher mode of this fiber is $\lambda_c = 1.23\ \mu$m, and the value of λ_0 is 1.3 μm. The fiber is pumped by the second harmonic of a mode-locked Nd:YAG laser. The average pump power is 2 W. The efficiency at which the pump light is coupled into the active fiber is 50%; that for the signal varies over the range 4–40%.

The spectral characteristics were studied on a grating monochromator with a resolution no worse than 0.5 nm, while the temporal characteristics were studied on an intensity autocorrelator by a phononless method with a resolution no worse than 15 fs (Ref. 2).

Figure 2(a) shows autocorrelation functions of the light intensity at the exit from a 55-cm active fiber for various efficiencies of the matching of the source fiber with the active fiber (6%, 8%, and 40%). Figure 2(b) shows corresponding spectra.

It can be seen from these results that when the coefficient γ, a measure of the matching of the two optical fibers, is low the pulse contracts to ~ 55 fs as it propa-

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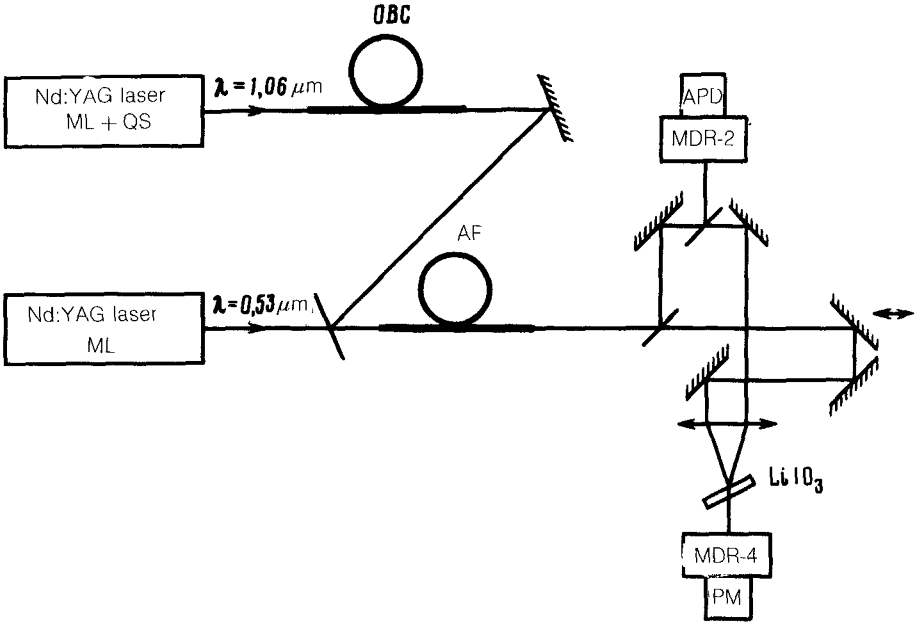

FIG. 1. Diagram of the experimental apparatus. ML—Mode-locked; QS—Q-switched; SMF—single-mode optical fiber; APD—avalanche photodetector; MDRs—monochromators; PM—photomultiplier; AF—active optical fiber.

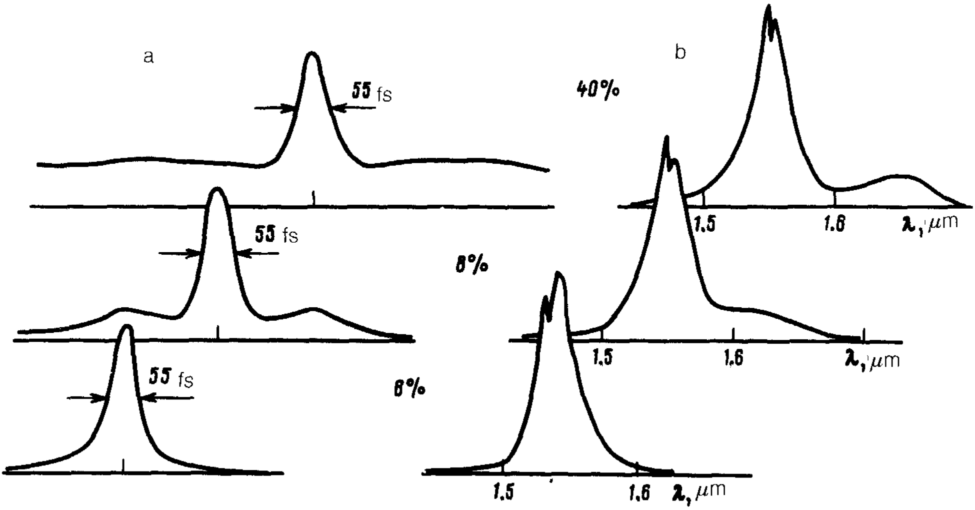

FIG. 2. a—Autocorrelation functions of the intensity of the amplified light for various efficiencies of the coupling of the light from the source fiber into the active fiber; b—corresponding spectra.

gates, and the corresponding spectral width is $\Delta\lambda = 35$ nm. The substructure in the spectrum near 1.54 μm results from an amplified spontaneous emission which has different interaction cross sections within the gain band because of a Stark splitting of resonant levels. This circumstance does not, however, cause a substantial change in the autocorrelation function, because of the long lifetime of the metastable level ($\sim 10^{-2}$ s).

The gain of the fiber amplifier with respect to the input pulse is 160. On the basis of this figure and the matching coefficient we estimate the energy of the output pulse to be 5 nJ.

As γ is increased, two side maxima appear in the autocorrelation function, as a result of a structural instability of the multisoliton pulse. A long-wavelength wing appears in the spectrum; such a wing is characteristic of stimulated Raman self-scattering.[3,4] As γ is increased, both the spectral resolution and the time resolution improve.

In order to make a more detailed study of the pulse propagation dynamics in the Stokes region, we altered the experimental apparatus slightly. The single-mode fiber serving as the source had a length of 100 m, so the length of the stimulated-Raman-scattering solitons became 120 fs (the increase in length resulted from the linear loss in the fiber). A piece of the same single-mode fiber 70 cm long was welded to the active fiber; the loss at the weld was less than 0.5 dB. As a result, the signal pulses passed initially through the passive single-mode fiber and then through the active fiber. The reason for choosing this arrangement was that by progressively shortening the active fiber we could follow the propagation of the dynamics of the nonlinear pulse. Figure 3 shows the length of the pulses in the region 1.7 μm, i.e., outside the Er^{3+} gain band, versus the length of the active fiber. We see that the pulse length remains unchanged, within the measurement error, over more than 20 dispersion lengths. Interestingly, the length of the pulse does not change in the Stokes wing, remaining at 55–60 fs, i.e.,

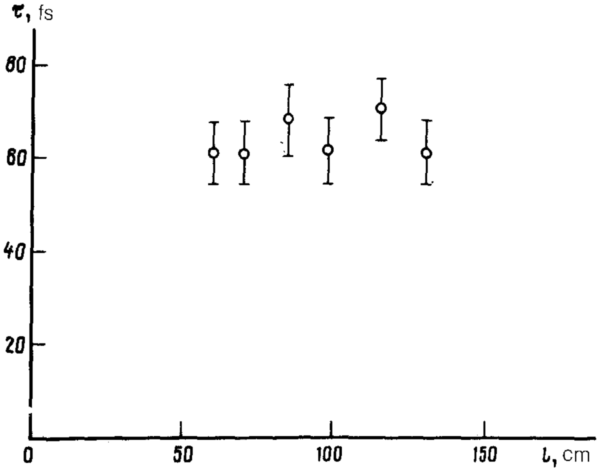

FIG. 3. Length of the pulses in the region $\lambda = 1.7\,\mu$m versus the length of the active fiber.

considerably shorter than in the case of "pure" stimulated Raman self-scattering in ordinary optical fibers, without resonant effects.[2,5]

The following qualitative picture can be drawn of the physical situation: In the first step of the amplification, the nonlinear pulse acquires energy while undergoing essentially no changes in temporal characteristics. The frequency pulling toward the center of the gain line leads to a structural stabilization of the pulse and prevents it from decaying into "colored" solitons. Once a certain threshold energy, greater than the energy of the fundamental soliton (by a factor of 10–15, according to our estimates), is reached, the pulse begins to contract, and it breaks up into several parts. As a result, a long-wavelength wing forms in the spectrum and moves into the Stokes region by virtue of stimulated Raman self-scattering.[4]

Numerical estimates support this interpretation of the results. In the region 1.54 μm in the active fiber used in these experiments, the second-order dispersion lengths of pulses 80 and 55 fs long are 11 and 5 cm, respectively; the gain length is $z_g = 1/\alpha = 6$ cm, where α is the gain, in reciprocal centimeters; and the shifts of the central frequency due to the stimulated Raman self-scattering for the 80-fs and 55-fs pulses in a fiber with a dispersion of 15 ps/(ns·km) are 10 nm/m and 40 nm/m, respectively.[6] The amplification process is thus not adiabatic, and the stimulated Raman self-scattering has a substantial effect on its dynamics.

An anomalous dispersion near the resonant-amplification line should affect the dynamics of the amplification. According to estimates, the change in the chromatic dispersion D due to this effect for this particular fiber is ± 5 ps/(nm·km) if the value of D in the absence of a resonant band is 15 ps/(nm·km).

We note in conclusion that the decrease in the gain when the optical fibers are coupled highly efficiently is a consequence of not only the resonant effect (gain saturation) but also a nonlinear effect: the transfer of energy into the Stokes region.

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