# Decay of femtosecond pulses in single-mode optical fibers

A. B. Grudinin, E. M. Dianov, D. V. Korobkin, A. M. Prokhorov, V. N. Serkin, and D. V. Khaïdarov
*Institute of General Physics, Academy of Sciences of the USSR*

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The dynamics of the decay of a 70-fs pulse into two solitons in a single-mode optical fiber has been studied experimentally for the first time. The results are used to estimate the relaxation time of the nonlinear response of quartz glass.

The nonlinear Schrödinger equation describing the propagation of picosecond solitons in single-mode optical fibers predicts a periodic change in the shape of the envelope of the wave packet in the case in which the pulse propagates in a multisoliton regime (Ref. 1, for example). With decreasing pulse length, however, the role played

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by higher-order dispersive and nonlinear terms—not included in the nonlinear Schrödinger equation—increases, with the result that several fundamentally new physical effects can occur. A study of these effects makes it possible to calculate numerical values of certain fundamental constants.

In this letter we report the first experimental study of the dynamics of the propagation and decay of a 70-fs multisoliton pulse in a single-mode optical fiber. The results can be used to calculate the relaxation time of a nonlinearity in quartz glass.

The source of the 70-fs light pulses is a stimulated-Raman-scattering source which uses a single-mode optical fiber and which is pumped by a Nd:YAG laser.[2] The light is coupled into a fiber with an effective core area $S = 11\ \mu m^2$ and a zero-chromatic-dispersion wavelength $\lambda_0 \cong 1.55\ \mu m$. A power of about 1.5 kW is coupled into the fiber.

Figure 1 shows correlation functions of the intensities at the entrance to the optical fiber and after 1, 2, 4, and 10 m of fiber. Figure 2 shows corresponding spectra. It can be seen from the results that over the first meter of the fiber the pulse contracts to ~25 fs; then, instead of recovering its shape (as predicted by the nonlinear Schrödinger equation), it splits spectrally and temporally into two parts. While the time interval increases with the length of the fiber (Fig. 3), the spectral interval is essentially independent of it. Mitschke and Mollenauer[3] recently published similar results and interpreted them as the decay of a multisoliton pulse into a soliton component and a nonsoliton component, accompanied by a continuous spectral shift of the central frequency of the soliton in the Stokes direction. Our results are evidence that both of these pulses are solitons. Over the first few meters of fiber, there durations are inde-

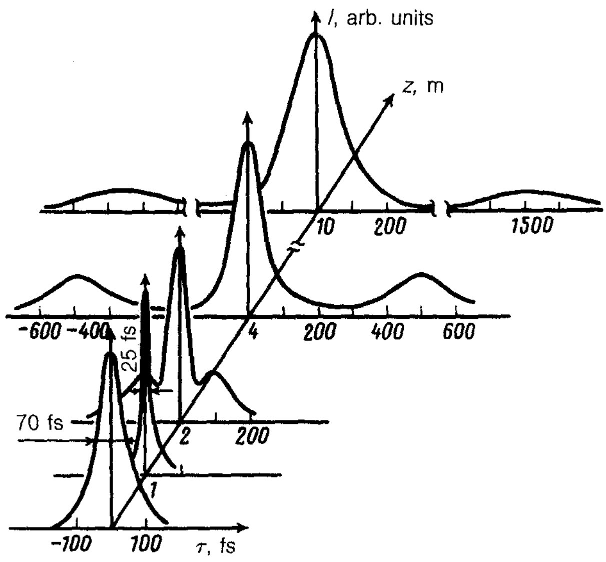


FIG. 1. Autocorrelation functions of the intensity at the entrance to the optical fiber and at a distance of 1, 2, 4, and 10 m.

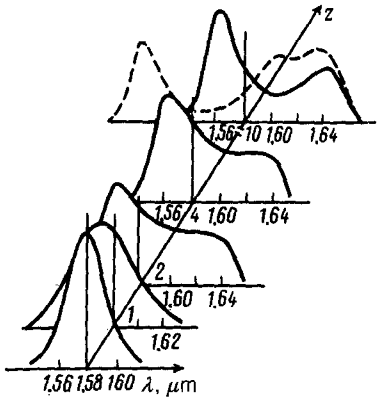


FIG. 2. Emission spectrum corresponding to the correlation functions in Fig. 1. The dashed line was calculated from Eqs. (1).

pendent of the length of the fiber, within the measurement error, but over large lengths they are found to increase slightly. In particular, at $z = 10$ m the duration of the pulse is about 40% greater than that at $z = 2$ m (Fig. 3). A behavior of this sort results from an energy loss by the soliton, due to both the linear optical loss and stimulated Raman self-scattering.[2] We should point out that a short-wavelength soliton (and one of shorter duration) was less stable than a long-wavelength soliton in terms of amplitude.

Mitschke and Mollenauer[3] showed in the particular case of a 500-fs pulse that the square of the time interval between the split components is proportional to the input power. In our experiments, this dependence resulted in some spreading and decrease in amplitude of a side peak (Fig. 1), because of an inadequate stability of the pump power.

To interpret the results, we first consider some numerical estimates. In the 1.58-

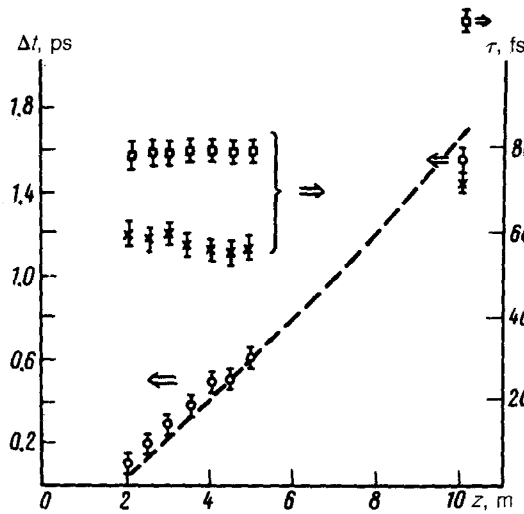


FIG. 3. Several properties as functions of the length of the fiber. ○—Time interval between the solitons that have decayed; ×—duration of high-frequency soliton; □—duration of low-frequency soliton [the dashed line was calculated from Eqs. (1)].

$\mu$m region, in the optical fiber used, the chromatic dispersion is $D = 1$ ps/(nm·km). The period and the power of the basic soliton, of duration $\tau_p = 70$ fs, are then $z_0 = \pi c \tau_p^2 / |D| \lambda^2 = 1.8$ m and $P_0 = \lambda S / 4 n_2 z_0 = 280$ W, respectively. A power $P \approx 1.5$ kW was coupled into the fiber, so that we find $N = \sqrt{P/P_0} \approx 2.3$ solitons in order of magnitude. The dispersion lengths of second and third orders are $z_d^{(2)} = \tau_0^2 / k'' = 115$ cm and $z_d^{(3)} = \tau_0^3 / k''' = 100$ cm, respectively, where $\tau_0 = [\tau_p / 2\ln(\sqrt{2}+1)] = 40$ fs, $k'' = d^2\tilde{\beta}/d\omega^2 = 1.4 \times 10^{-29}$ s$^2$/cm, and $k''' = d^3\tilde{\beta}/d\omega^3 = (0.7 \pm 0.3) \times 10^{-42}$ s$^3$/cm. Here $\tilde{\beta}$ is the propagation constant of the fundamental mode. The nonlinear length is $z_{nl} = z_0 / N^2 = 23$ cm. These estimates show that a correct analysis of the results requires consideration of higher-order dispersive and nonlinear effects.

Several theoretical papers[4–6] have dealt with the propagation dynamics of femtosecond pulses in single-mode optical fibers. Effects of the appearance of envelope shock waves,[4] a third-order dispersion,[5] and a stimulated Raman self-scattering of the pulse[6] have been taken into account separately. None of these papers, however, describes the experimental results satisfactorily.

At present, we do not have a comprehensive theory for the propagation of a multisoliton femtosecond pulse in a single-mode optical fiber which simultaneously incorporates all of the effects (the relaxation and dispersion of the nonlinear response of the medium, the third-order dispersion, stimulated Raman scattering, and so forth). As a "first approximation" we accordingly consider the self-effect of femtosecond wave packets in a nonlinear dispersive medium on the basis of the following model:

$$i\frac{\partial \Psi}{\partial z} = \frac{1}{2}\frac{\partial^2 \Psi}{\partial \tau^2} + R\,\delta n \Psi - i\gamma R \frac{\partial}{\partial \tau}(\delta n \Psi) - i\beta \frac{\partial^3 \Psi}{\partial \tau^3},$$

$$\frac{T_1}{\tau_0}\frac{\partial}{\partial \tau}\delta n + \delta n = |\Psi|^2, \qquad (1)$$

where the relaxation of the nonlinear response of the medium is taken into account phenomenologically. Here $\Psi = E/E_0$ is the normalized amplitude of the envelope of the wave packet, $\tau = [(t - z/v_{\lim})/\tau_0]$, $R = N^2$, $\gamma = (T/\pi\tau_0)$, and $\beta = (\frac{1}{6})(k'''/k''\tau_0)$ $T$ is the optical period of the field oscillations.

The relaxation time of the electron nonlinearity, $T_1$, can be calculated through a numerical solution of system (1). The procedure for determining $T_1$ can be outlined as follows: Since the range of possible values of $\beta$(0.1–0.3) is known, we vary $T_1$ to bring the output spectra and the dependence $\Delta t(z)$ into a qualitative agreement. The results of a numerical simulation of this sort are shown in Figs. 2 and 3 by dashed curves, for the case $R = 5$, $\gamma = 0.04$, $\beta = 0.2$, and $T_1/\tau_0 = 0.05$. The good qualitative agreement of the theoretical and experimental curves makes it possible to estimate the nonlinearity relaxation time $T_1$: 2–4 fs.

We would like to stress that the theoretical model which has been used here is rather primitive and ignores many factors. In particular, since the working wavelength is close to the zero-dispersion point, the quantity $R$ depends on $\lambda$ even within the envelope of the wave packet. Regarded as a first step, however, this model seems completely suitable. It makes possible a more systematic theoretical and experimental study of the processes involved in the propagation of femtosecond pulses in optical fibers, both to learn about the propagation dynamics and to observe new physical effects.

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