Stimulated-Raman-scattering excitation of 18-fs pulses in the 1.6-μm region during pumping of a single-mode optical fiber by the beam from a Nd:YAG laser ($\lambda = 1.064$ μm)

A. B. Grudinin, E. M. Dianov, D. V. Korobkin, A. M. Prokhorov, V. N. Serkin, and D. V. Khaĭdarov
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

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This letter reports the first results of a study of the excitation of ultrashort pulses in cascade stimulated Raman scattering in a single-mode optical fiber. The use of multisoliton contraction in a fiber with a shifted dispersion has made it possible to produce light pulses containing just barely more than three optical oscillation periods.

A few years ago, Isaev *et al.*[1] proposed and derived a theoretical basis for a method of generating ultrashort light pulses in cascade stimulated Raman scattering in a region of a single-mode optical fiber with a negative chromatic dispersion. Since no experimental studies have been carried out on this topic, it appeared to us to be extremely interesting and worthwhile to experimentally evaluate the possibility of generating ultrashort light pulses from a spontaneous Raman-scattering noise when a single-mode optical fiber was pumped by light from a solid-state Nd:YAG laser (the most common and most readily available laser).

Figure 1 shows the experimental layout. The pump source is a Nd:YAG laser operating with simultaneous mode locking and Q switching. The length of the pulse train is 200 ns; the length of a pulse in the train is 150 ps; and the pulsed power is about 600 kW. The laser output is coupled into a single-mode optical fiber with a core diameter $2a = 8$ μm, a difference $\Delta n = 3 \times 10^{-3}$ between the refractive indices of the core and the cladding, and a zero-chromatic-dispersion wavelength $\lambda_0 = 1.32$ μm.

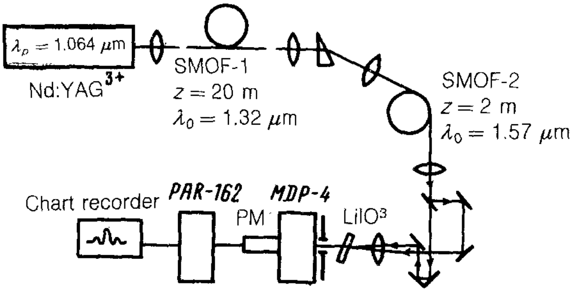

FIG. 1. The experimental layout.

Figure 2 shows a spectrum of the stimulated Raman scattering in the test sample at the pump power of about 5 kW in the fiber. We study the temporal characteristics of the light with the help of an intensity autocorrelator by a background-free method and also with the help of an image-converter camera with a linear sweep. (Thanks to the sharp focusing of the light on the $LiIO_3$ crystal, the spectral width of the matching of the crystal is 140 nm.) Figure 3a shows an autocorrelation function of the light intensity at the exit from the fiber in the region 1.6 μm. The width of the correlation function is 110 fs; from this figure, under the assumption that the pulse has a $\mathrm{sech}^2 x$ shape, we find a pulse length of 70 fs. The measured power of the pulse is ~10 kW. A characteristic feature of this mechanism for generating ultrashort light pulses is that the pulse length is independent (within certain limits) of the pump power: As the pump power is raised, there is simply an increase in the pedestal of the correlation function, while the length of the central peak remains the same. Measurements with the image-converter camera (the second harmonic of the light, with $\lambda = 1.6$ μm, was applied to the camera) show that the Stokes pulse in the region of anomalous dispersion of the fiber consist of distinct peaks shorter than 5 ps (the time resolution of the camera). As the input power is reduced, the number of peaks decreases, while the power in an individual peak remains essentially constant.

The general features of the mechanism for the generation of the ultrashort light pulses in this case can apparently be described as follows. A 150-ps laser pump pulse excites a cascade stimulated Raman scattering, which develops from spontaneous

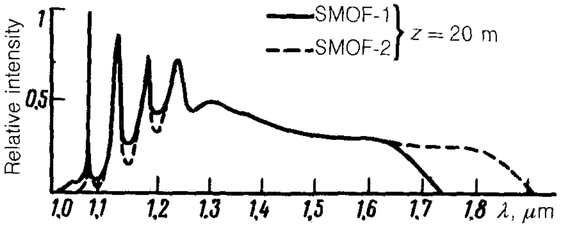

FIG. 2. Spectra of stimulated Raman scattering in single-mode optical fibers with various zero-chromatic-dispersion wavelengths.

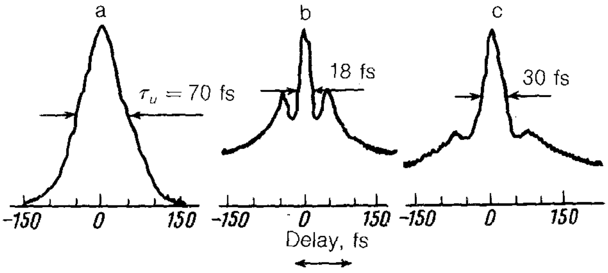

FIG. 3. Intensity correlation functions. a—The single-stage generation layout; b,c—the two-stage layout. The wavelength is 1.6 μm.

noise. In the region of positive chromatic dispersion, the envelope of the pulses at the Stokes frequencies has a noisy substructure with a typical length of about 50 fs for a noise peak. That length is determined by the shape of the stimulated-Raman-scattering-gain line of fused quartz glass. A fourth Stokes component of the stimulated Raman scattering ($\lambda \sim 1.30$ μm) serves as a pump for a wave in a region of negative chromatic dispersion of the fiber. At a certain pump power, the threshold condition for the gain becomes satisfied for only one or a few peaks, with a length on the order of 50 fs. As a result, a subpicosecond light pulse with a spectral width determined by the shape of the stimulated-Raman-scattering gain line is shaped in the region of negative dispersion. At such a significant spectral width, the low-frequency components in the spectrum of the pulse are amplified in the field of high-frequency components, with the result that energy is transported into the Stokes region. This circumstance is one of the reasons for the formation of a continuous spectrum in the region of negative dispersion of the group velocities of the single-mode fiber. We call this new self-effect "stimulated-Raman self-scattering of ultrashort light pulses." This effect was originally observed in Ref. 2, and those observations were confirmed in a study published recently.[3]

As the pump power is raised, (first) the existing pulses at the Stokes frequency "shed" power into the IR region in the region of negative dispersion, and (second) new pulses appear. These new pulses are created by those pump peaks for which the threshold-gain condition has been satisfied.

If we assume that the pulses which are formed are solitons (and this assumption is supported by the length and power of these pulses and their insensitivity to slight changes in the pump power), then we could easily explain the fact that the long-wave spectral boundary on stimulated Raman scattering in a single-mode optical fiber 20 m long with $\lambda_0 = 1.32$ μm is at 1.75 μm (the solid line in Fig. 2), while that in a fiber of the same length with $\lambda_0 = 1.57$ μm is at 1.9 μm (the dashed line in Fig. 2). Specifically, if we note that the power and length of a soliton are related ($P\tau^2 = \text{const}$), and if we note that the distance over which the Stokes wave interacts with the pump depends on the difference between their group velocities $[z_{\rm coh} = \tau_u/(v_s^{-1} - v_p^{-1})]$, we can show that the gain for the Stokes wave is inversely proportional to the chromatic disperson of the single-mode fiber ($Gk'' = \text{const}$).

The obvious way to reduce the pulse length even further is to switch to a two-stage generation arrangement. As a second fiber we chose a single-mode optical fiber with a shifted dispersion, so that the chromatic dispersion at $\lambda = 1.6\ \mu\text{m}$ was 2 ps/(nm·km). Figure 3b shows the intensity correlation function of measurements carried out at the exit from a second fiber, 2 m long; this result can be interpreted as a bound state of solitons 18 fs long, i.e., with a length just barely greater than three optical oscillation periods. (The period of an optical oscillation at the wavelength 1.6 μm is 5.3 fs.) By varying the conditions for the pumping of the second fiber, we varied the shape of the correlation function, as illustrated by Fig. 3c.

To determine the physical picture for the formation of stable soliton-like wave packets with an envelope length on the order of three or four optical oscillation periods in optical fibers, we made a theoretical study of the basic physical mechanisms which limit the length of the pulses that are formed. Our calculations were carried out in the generalized method of slowly varying amplitudes.[1] We took into consideration the chromatic dispersion of up to third order, the relaxation of the nonlinearity, and the Raman self-scattering of the pulse. Numerical studies showed that the effects which are most important in imposing a limiting length of two or three field oscillation periods on the pulses that are formed are the relaxation of the nonlinearity and the chromatic dispersion of higher orders.

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