Nonlinear mode coupling in multimode optical fibers; excitation of femtosecond-range stimulated-Raman-scattering solitons

A. B. Grudinin, E. M. Dianov, D. V. Korbkin, A. M. Prokhorov, and D. V. Khaïdarov

Institute of General Physics, Academy of Sciences of the USSR

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The excitation of 70–100-fs solitons has been observed experimentally in multimode optical fibers for the first time. In the nonlinear regime, the energy propagates in the fundamental mode, and the power of the fundamental soliton is about 30 kW.

Mode coupling in long, low-loss, multimode optical fibers is known to lead to a nearly uniform distribution of energy among modes.[1] It has also been learned that under certain conditions in a nonlinear system the energy will become distributed among only a few lowest modes.[2] There is accordingly much practical and scientific interest in learning about the temporal and spatial characteristics of intense radiation which is propagating along a multimode optical fiber.

Since the intensity of stimulated Raman scattering in an optical fiber is fairly high, we would quite obviously consider the use of the spectral, temporal, and spatial characteristics of stimulated Raman scattering in a multimode fiber to solve this problem.

Let us summarize the experimental layout.

The beam from a Nd:YAG laser with simultaneous mode locking and Q switching ($\tau_p = 150$ ps $P_{peak} = 600$ kW, $\lambda = 1.064$ μm) is coupled into the multimode optical fiber. The temporal characteristics are measured by a background-free method at an intensity autocorrelator (the time resolution of the autocorrelator is 12–15 fs). The spectral characteristics are measured by an MDR-4 monochromator and a germanium photodiode. The spatial characteristics are measured by scanning a single-mode optical fiber with a known field distribution for the fundamental mode over the exit end of the multimode fiber.

Line 1 in Fig. 1 is the spectrum of stimulated Raman scattering in a multimode fiber with a parabolic refractive-index profile. The maximum difference between the indices of the core and the cladding is $\Delta n = 13 \times 10^{-3}$; the core diameter is $2a = 38$ μm; and the length is 50 m. The spectrum is continuous in the region of negative dispersion of the group velocities ($k'' < 0$): The nature of the spectrum is the same as in single-mode optical fibers. (For comparison, line 2 shows the spectrum of stimulated Raman scattering in a single-mode fiber.) Since the continuous spectrum of the stimulated Raman scattering in the single-mode fiber results from the onset of a modulational instability, followed by a frequency conversion due to a stimulated Raman

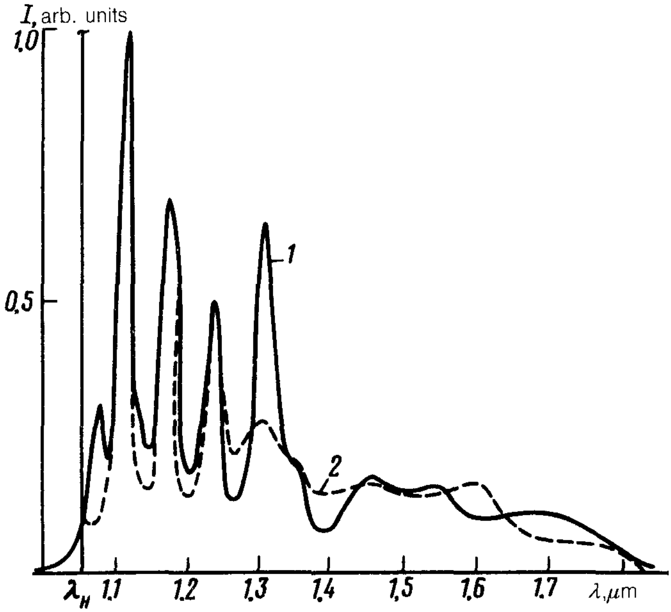

FIG. 1. Spectra of cascade stimulated Raman scattering. 1—In a graded-index multimode optical fiber; 2—in a single-mode optical fiber.

self-scattering of the pulses, with the result that femtosecond-range stimulated-Raman-scattering solitons are formed,[3] it might be suggested that stimulated-Raman-scattering solitons exist in multimode fibers also.

Measurements of the temporal structure of the stimulated Raman scattering in the multimode fiber confirm this suggestion. Line 1 in Fig. 2 is the autocorrelation function of the intensities at the exit from a multimode fiber 50 m long in the 1.6-μm region. The length of the pulse is 90 fs if we assume that the pulse has a sech^2 shape. It should be noted that such short light pulses are produced over a wide spectral region, as illustrated by the inset in Fig. 2, where line 1 shows the length of the pulses, and line 2 the contrast of the correlation function.

Measurements of the duration in a 500-m length of optical fiber (line 2 in Fig. 2) revealed that the pulses which are formed are stimulated-Raman-scattering solitons. The increase in the pulse duration results from a dissipation of energy because of the linear optical loss.

Measurements of the intensity distribution at the end of the fiber yielded results which agree qualitatively with the results of Ref. 4. If the field at the pump wavelength ($\lambda = 1.064\ \mu$m) at the end of the multimode fiber is represented as a superposition of many modes (about 100; see line 1 in Fig. 3), the intensity distribution in the 1.6μm region corresponds to the fundamental mode (line 2 in Fig. 3). Confirmation of a single-mode regime in the multimode fiber comes from measurements of the spatial coherence of the field at the end of the fiber. The experimental results provide evidence

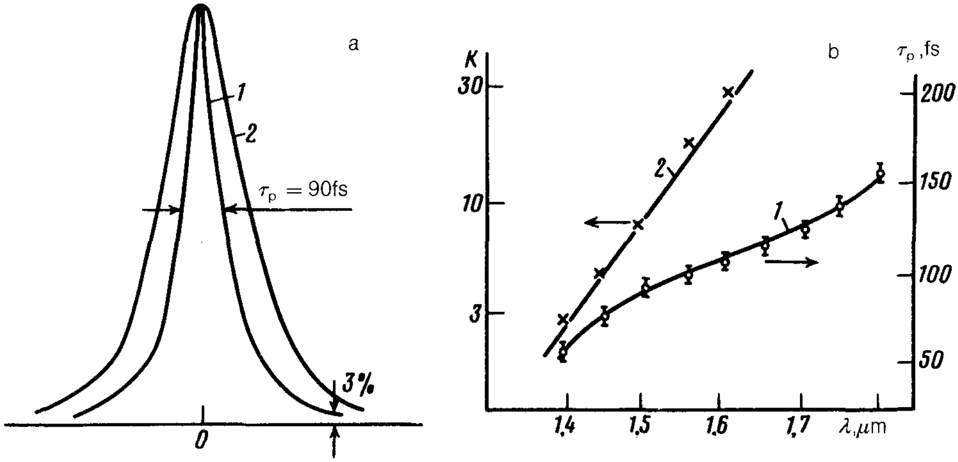

FIG. 2. a: Autocorrelation functions of the light in the 1.6-μm wavelength region in multimode optical fibers. 1—The length of the fiber is 50 m; 2—500 m. b: The pulse length τ (1) and the contrast of the autocorrelation function K (2), versus the wavelength.

that the field is spatially coherent, i.e.. that the Stokes wave propagates in the fundamental mode in the region of negative chromatic dispersion of the multimode fiber.

This fact has two basic consequences, in our opinion. First, there is the realistic possibility of utilizing multimode fibers in high-speed communication links and in devices for sensing physical fields. Second, the power in the fundamental stimulated-Raman-scattering soliton is increased significantly. For example, the power of a 90-fs pulse is 30 kW in this case, while in a single-mode fiber a stimulated-Raman-scattering soliton of the same duration would have a peak power of about 5 kW. This power

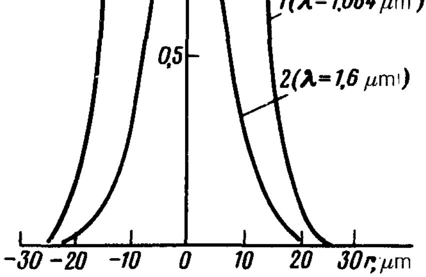

FIG. 3. Intensity distribution at the end of a multimode optical fiber at various wavelengths. 1—λ = 1.06 μm; 2—λ = 1.6 μm.

could apparently be raised to 100 kW by choosing an appropriate fiber.

With regard to the physical mechanism for the excitation of femtosecond-range stimulated-Raman-scattering solitons in a multimode fiber, the picture is not clear at this point. We will accordingly list several experimental facts which may be of assistance in reaching an understanding of the essence of this effect in the future.

1. The temporal characteristics of the stimulated Raman scattering in a multimode optical fiber in the region of negative dispersion of the group velocities are completely similar to the temporal characteristics of stimulated Raman scattering in a single-mode fiber: In the region of a small but negative chromatic dispersion, the intensity autocorrelation function corresponds to a modulational instability, and the contrast of the autocorrelation function increases with increasing wavelength.

2. The field distribution at the end of a multimode fiber in the region of positive chromatic dispersion corresponds to a superposition of many modes. The typical field strength at the end decreases with increasing wavelength. In the region of negative chromatic dispersion, beginning at a certain wavelength (about 1.5 μm), the energy is carried by only a single mode: the fundamental mode. A decrease in the number of propagating modes in the course of a cascade stimulated Raman scattering of modes was first observed in Ref. 4. This effect has been confirmed in a recent paper.[5] In those papers, this spatial behavior of the field was explained on the basis of a self-focusing effect which arises in a waveguiding medium when the power is several orders of magnitude below the threshold for self-focusing in a bulk medium. That explanation, however, lacks a satisfactory theoretical foundation and thus requires further research.

3. The nature of the field distribution is essentially independent of the pump power when the threshold value of this power is reached (at the threshold, the power in the Stokes components is comparable to the pump power).

4. The nature of the field distribution is also independent of the length of the fiber: As the length of the fiber is varied from 10 m to 500 m, the field distribution remains the same at wavelengths in the region $\lambda > 1.5$ μm. We believe that this behavior is a consequence of a nonlinear mode coupling, which prevents a diffusion of energy to higher-index modes. However, the physical mechanism for this coupling is not yet clear.

In conclusion we wish to stress that the effect discovered here—the excitation of femtosecond-range stimulated-Raman-scattering solitons in multimode optical fibers—will make it possible to increase the power of ultrashort pulses by nearly an order of magnitude. It will also make possible a more detailed study of the nonlinear dynamics of femtosecond-range solitons.

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