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SECOND WORKSHOP ON

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STIMULATED-RAMAN CONVERSION OF MULTISOLITON PULSES IN QUARTZ OPTICAL FIBERS

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vibrational substructure of the electronic terms. Consequently, in intense fields, in which the condition for the existence of a quasicontinuum is satisfied (the Stark broadening of the levels is greater than the characteristic distance between the adjacent states), we should expect changes in the power-law dependence of the ion formation probability on the UV intensity. We are apparently observing such a change in the formation of the CF_3I^+ ion during vibrational excitation of the CF_3I molecule to the level $3\nu_1 \approx 3000\ cm^{-1}$.

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Stimulated-Raman conversion of multisoliton pulses in quartz optical fibers

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A mechanism of stimulated-Raman amplification from an incident wave self-induced by a phase self-modulation is proposed. When a fiber is pumped with light with $\tau = 30$ ps at $\lambda = 1.5$–$1.65\ \mu m$, single pulses with $\tau = 200$ fs and $P = 56$ kW are produced at the Stokes frequency.

Single-mode glass optical fibers, used as a nonlinear medium, can perform a phase self-modulation of light pulses in a uniform manner over the beam cross section. This self-modulation leads to a significant expansion of the spectra of these pulses. When frequency-modulated pulses of this sort propagate through a medium with a negative group-velocity dispersion ($dV_g/d\lambda < 0$), they will undergo a self-compression.[1] Quartz optical fibers have[2] $dV_g/d\lambda < 0$ at $\lambda > 1.3\ \mu m$, and this property has been exploited[3–5] to achieve both soliton propagation regimes and a self-compression of picosecond pulses. The possibility of a nonlinear conversion of a three-soliton pulse into a single-soliton pulse involving 90% of the energy during a stimulated-Raman amplification

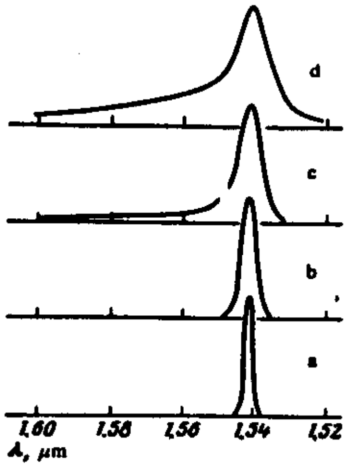

FIG. 1.

from a monochromatic nucleation pulse with a strictly given amplitude was analyzed theoretically by Vysloukh and Serkin.[6] The production of a nucleating pulse of this type on the Stokes side of the pump runs into serious experimental difficulties. This type of nonlinear conversion is important for producing high-contrast ultrashort pulses containing all the converted energy.

In the present experiments, a 250-m length of single-mode fiber is pumped by a parametric light source with $\tau = 30$ ps and a pulse repetition frequency of 100 Hz, tunable over the spectral interval 0.74–1.9 μm. The light leaving the fiber enters a correlator in which the pulse length is determined from measurements of the zero-phonon autocorrelation functions of the intensity during second-harmonic generation in a $LiIO_3$ crystal 1 mm thick.[4] The light leaving the correlator enters a monochromator, which is used in the method of Ref. 7 to measure the autocorrelation functions of the various frequency components of the light leaving the fiber.

Figure 1, a–d, shows spectra of the light at the exit from the fiber ($\lambda_p \approx 1.54\ \mu m$) as the power in the pulse injected into the fiber is systematically raised to 900 W (on the basis of the average power and the length of the pulse). That pump power P_p which leads to a broadening of the spectrum due to a phase self-modulation (Fig. 1a) is 50 W, according to an estimate which ignores the dispersion and which is based on the standard nonlinear increment in the refractive index, $n_2 = 3.2 \times 10^{-16}\ cm^2/W$, and the properties of the fiber. As P_p is raised to 100 W (Fig. 1c), a long-wave Stokes wing appears in the previously symmetric spectrum (Fig. 1, a and b). At $P_p \approx 800$ W, this Stokes wing contains up to 50% of all the light energy.

What factors give rise to the Stokes wing? As the pulse propagates through the fiber, its spectrum begins to broaden as a result of phase self-modulation (Fig. 1, a and b); the symmetry of the spectrum is evidence of a symmetry of the traveling pulse. Because of the joint effects of the phase self-modulation and the group dispersion at $\lambda_p = 1.54\ \mu m$, the pulse traveling through the lightguide begins to be compressed,

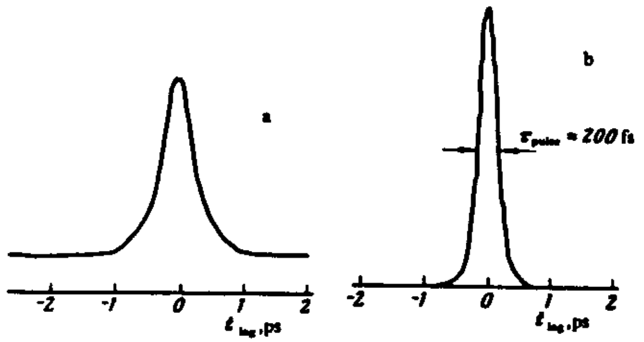

FIG. 2.

forming an intense narrow peak[3,4] against the background of a broad pedestal, according to the theoretical predictions of Ref. 5. Estimates from the equations of Refs. 3 and 5 show that at $P_p \simeq 100$ W [where the Stokes wing appears in the spectrum (Fig. 1c)] the order of the soliton is $N \simeq 30$, the self-compression reaches a maximum over a distance of 200–300 m, and the length of the compressed peak is ~ 120 times shorter than the pulse entering the fiber.

Fused quartz has a remarkable property: a continuous spectrum of inhomogeneously broadened vibrational resonances stretching essentially from 0 to more than 1000 cm^{-1}. Even for a Stokes shift $\Delta\nu = 55$ cm^{-1}, the intensity in the spectrum of the spontaneous Raman scattering is only 1.5 times lower than the maximum intensity ($\Delta\nu = 440$ cm^{-1}).

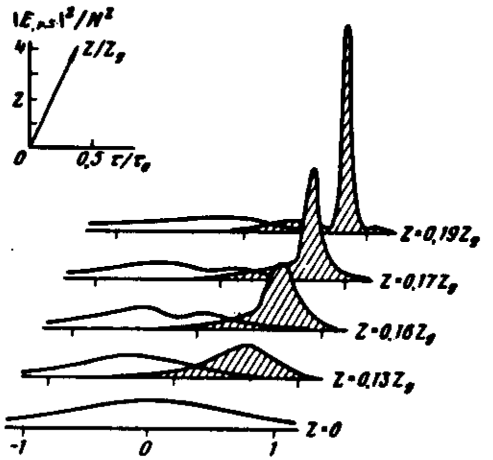

FIG. 3. Results of a numerical simulation which illustrate the nonlinear dynamics of the amplification of a nucleating Stokes pulse $|E_s(0,\tau)|^2 = 0.1 N^2 \operatorname{sech}^2(\tau/\tau_0)$ in the field of a pump pulse $|E_H(0,\tau)|^2 = N^2 \operatorname{sech}^2(\tau/\tau_0)$ for $N = 5$, according to calculations based on the system of equations from Ref. 6. The scale time of the group delay of the Stokes and pump pulses over the dispersion length is $\nu = z_g |(1/v_s) - (1/v_H)|/\tau_0 = 6$, where $z_g = \tau_0^2/(\partial^2 k/\partial\omega^2)$, and τ_0 is the initial length of the pump pulse. Shown here are the "burnup" of the pump pulse (unhatched; $z \approx 0.13 Z_g$), the conversion of the stimulated-Raman pulse to a symmetric shape (hatched) in the region $z > 0.17 Z_g$, and the isolation of a nonsoliton component from it at $z > 0.19 z_g$.

Part of the spectrum of the compressed pump peak falls in the region of stimulated-Raman amplification [for a Gaussian pulse with $\tau = (30$ ps$)/120 = 0.25$ ps, the spectral density for $\Delta\nu = 55$ cm^{-1} is ~ 0.1 of its value at the center of the line]. The pump pulse thus forms a rather intense nucleating pulse at the Stokes frequency, and the stimulated-Raman amplification from this nucleating pulse rapidly reaches saturation. At our values of P_p, the threshold for stimulated-Raman amplification from the spontaneous noise is not reached.

During the formation and propagation of the Stokes pulse, it begins to lag behind the pump pulse, by virtue of the property $dV_g/d\lambda < 0$ (at $\Delta\nu = 55$ cm^{-1} the lag is ~ 0.3 ps/m), and thus "eats out" the trailing part of the pedestal of the pump pulse. As P_p is raised, the stimulated Raman scattering appears earlier, and the Stokes pulse can therefore acquire more energy. Furthermore, according to the numerical simulation of Ref. 6, there may be nonlinear capture of the pump and Stokes pulses, resulting in more-efficient energy exchange.

In summary, we attribute the Stokes wing that appears in the emission spectrum (Fig. 1, c and d) to a nonlinear Raman conversion of the pump pulse, which, as it forms in a natural way over the length of the fiber (not necessarily at the point of maximum compression), begins to convert into a Stokes pulse. Figure 2a shows the autocorrelation function at the pump frequency ($\lambda_p = 1.54$ μm; Fig. 1d). Figure 2d shows an autocorrelation function corresponding to the Stokes wing of the spectrum in Fig. 1d, for $\Delta\nu = 55$ cm^{-1}. This correlation function reflects a single Stokes pulse without a pedestal, with $\tau \simeq 200$ ps and $P = 56$ kW (calculated from the energy of the Stokes wing).

In contrast with the method of "soliton compression" at the pump frequency,[3] the method demonstrated by the experiments reported here can be used to produce high-energy femtosecond light pulses without a pedestal.

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