Picosecond structure of the pump pulse in stimulated Raman scattering in a single-mode optical fiber

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The temporal characteristics of the spectrally broadened pump light (Nd:YAG laser with $\tau_p = 60$ ps) have been studied during stimulated Raman scattering in a single-mode optical fiber. Spectral filtering of the light emerging from the fiber makes it possible to obtain single pulses 2–3 ps long.

Recently developed methods for producing ultrashort pulses in the pico- and subpicosecond ranges make use of a phase self-modulation in an optical fiber, which results in a broadening of the spectrum of the light, followed by a contraction of the

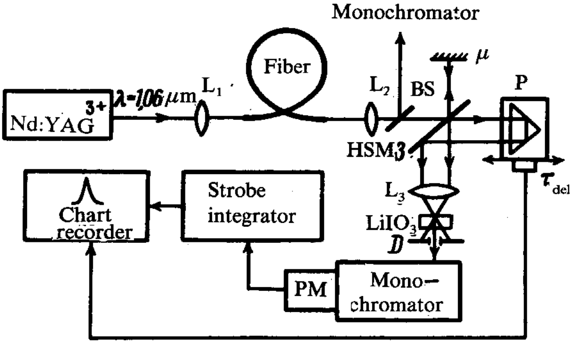

FIG. 1. The experimental apparatus. L_1–L_3—Lenses; BS—beam splitter; M—mirror; P—prism; τ_{tel}—device which detects the displacement of prism P; HSM—half-silvered mirror; D—diaphragm.

pulse with a frequency sweep in a medium with an anomalous dispersion[1,2] ($\partial^2\omega/dk^2 > 0$). In Ref. 3 we reported a fifteen-fold contraction of a 60-ps pulse of light from a Nd:YAG laser in an arrangement with a diffraction grating. In those experiments the pump power level in the fiber was limited by the threshold for the stimulated Raman effect.

Figure 1 shows the apparatus used in the present experiments. The pump laser and the optical fiber were the same as in Ref. 3 (a cw-pumped Nd:YAG laser in *Q*-switched operation with active mode locking emits a train of ultrashort pulses 60 ps long at half-maximum, and the optical fiber is 10 m long). The light emerging from the fiber is sent to a monochromator for the measurements of the spectrum and to a correlator for measurements of the temporal characteristics of the ultrashort pulses. These characteristics are determined from the autocorrelation function obtained through second-harmonic generation in a noncollinear interaction of beams in a $LiIO_3$ crystal. The second-harmonic light goes from the correlator to the monochromator; the correlation functions are recorded at a 5-nm spectral width of the monochromator slit. The photomultiplier output signal is fed through a strobe integrator to the *Y* coordinate of a chart recorder.

As the peak power (P_{pump}) in the optical fiber is increased to a level slightly below that at which the stimulated Raman effect occurs, the spectrum of the light emerging from the fiber is broadened to ≈ 10 cm^{-1} by the phase self-modulation. As the pump power is raised further, to $P_{pump} \gtrsim P_{cr}$, the Stokes component of the stimulated Raman scattering is observed, shifted $\Delta\nu \approx 440$ cm^{-1} from the pump frequency and having a spectral width ≈ 80 cm^{-1} (P_{cr} corresponds to the case in which the power level of the Stokes component at the output from the fiber is equal to the power level of the pump beam). An estimate[4] of P_{cr} for our case yields ~ 1.5–2 kW. The onset of the stimulated Raman scattering is accompanied by the simultaneous appearance of an intense pedestal in the spectrum of the pump. This pedestal stretches into the anti-Stokes region, to $\Delta\nu \approx 400$ cm^{-1}, and in the Stokes region it overlaps the spectrum of the stimulated Raman scattering (the spectral density of the light at $\Delta\nu = 100$ cm^{-1} is $\sim 10^{-2}$ of the corresponding value at $\lambda = 1.064$ μm).

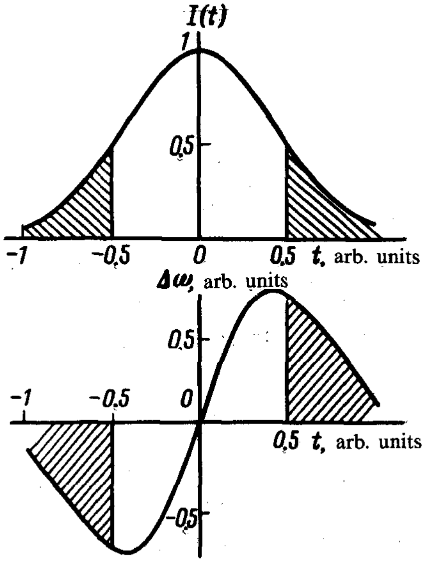

FIG. 2.

Figure 2 shows autocorrelation functions of the pump light. The dashed curve corresponds to the case of a low pump power in the fiber ($P_{\text{pump}} \ll P_{\text{cr}}$); curve 1 corresponds to the case of an efficient stimulated Raman scattering ($P_{\text{pump}} > P_{\text{cr}}$). An autocorrelation function with three peaks corresponds to a pump pulse after its central part has been "eaten away" by the stimulated Raman scattering, as sketched in Fig. 3. We are essentially left with two pulses from the smooth pump pulse; these two pulses or

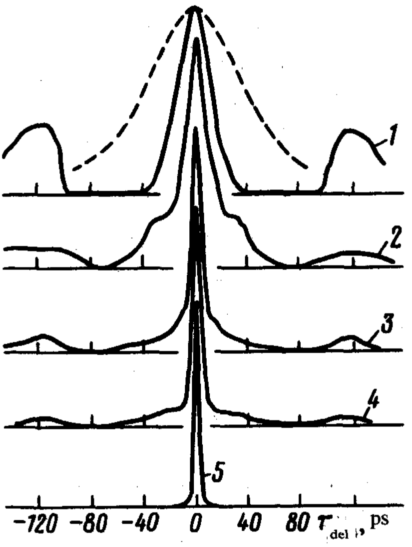

FIG. 3. Time dependence of the frequency shift, $\Delta\omega(t)$ (b), due to phase self-modulation for a Gaussian pulse (a).

"fragments" are the hatched regions in Fig. 3a, which have a peak power $\sim P_{\text{cr}}$. The distance between these pulses depends on the extent to which P_{pump} exceeds P_{cr}. The width of the central peak of the autocorrelation function is 31 ps (curve 1 in Fig. 2) and corresponds to a fragment length ≈ 20 ps. The central part of the pulse, with a linear frequency sweep, is converted into stimulated Raman scattering (Fig. 3b). The stimulated Raman scattering thus prevents an effective contraction of the pump pulse emerging from the optical fiber in a medium with an anomalous dispersion. We might note, however, that in the stimulated Raman effect the frequency sweep in the pump pulse is transferred to the stimulated-Raman pulse,[5] and there may be a pronounced contraction of the stimulated-Raman pulse with a high contrast in a medium with an anomalous dispersion. On the other hand, the fragments of the pump have a negative frequency sweep (the frequency decreases toward the end of the pulse), and in principle they may undergo a self-contraction in the region of the positive dispersion ($\partial^2\omega/\partial k^2 < 0$) of our optical fiber ($\lambda < 1.33$ μm).[6] Estimates show that the optical fibers would have to be $\gtrsim 1$ km long for any substantial contraction of these fragments. In order to study the mechanism for the appearance of the intense and broad pedestal in the light spectrum at the exit from the optical fiber, we measured the autocorrelation functions at various frequency components in the part of the spectrum on the anti-Stokes side of the pump. The frequency components in the spectrum were obtained by tuning the monochromator and rotating the crystal used to generate the second harmonic (the spectral width of the matching is ~ 6 nm). Curves 2–5 in Fig. 2 show autocorrelation functions corresponding to the anti-Stokes frequency components shifted 9, 36, 72, and 104 cm^{-1}, respectively, with respect to λ_{pump}. With increasing $\Delta\nu$, the width of the central peak of the autocorrelation function decreases, while the intensity of the side peaks falls off; these side peaks are missing altogether from curve 5. The width at half-maximum of curve 5 is 3.6 ps (the corresponding pulse length is $\tau_p \approx 2.5$ ps). The high contrast of this autocorrelation function indicates that the filtering of the light emerging from the fiber will make it possible to obtain a single pulse with $\tau_p \approx 2$–3 ps.

Wide-band Stokes-anti-Stokes generation in an optical fiber can also be achieved through four-wave mixing with phase matching of the interacting waves.[7] Since the power level of the fragments of the pump remains $\approx P_{\text{cr}}$ as P_{pump} is raised, however, the four-wave process would also have to occur at $P_{\text{pump}} < P_{\text{cr}}$, but we do not observe this process in our experiments.

The apparent reason for the generation of such short pulses at a frequency displaced from the pump frequency is the formation of steep (along the time scale) fronts in the stimulated-Raman and pump pulses as the pump light is eaten away by the stimulated Raman light[8] (Fig. 3). Because of the phase self-modulation, there should be an abrupt change in the phase at such a front and a corresponding frequency shift (which is not reflected in Fig. 3). A difference between the group velocities of the stimulated-Raman and pump beams might play an important role in shaping the temporal fronts of the pulses and also the spectrum by virtue of phase self-modulation (since phase self-modulation is determined by the resultant intensity of the stimulated-Raman light and the pump).

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