Generation of high-energy solitons of stimulated Raman radiation in fiber light guides

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The possibility of forming stationary ultrashort pulses of stimulated Raman radiation, high-energy solitons, which store essentially all of the pumping energy and which also have a much higher amplitude and, therefore, shorter length than the pumping pulses, in thin fiber light guides is demonstrated.

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Optical solitons have now become not only an object for theoretical studies but also for experimental studies.[1,2] Soliton regimes of propagation of laser radiation in fiber light guides (FL) open up new possibilities for forming ultrashort pulses with controllable parameters, required for subpicosecond spectroscopy and ultrafast transmission of information along fiber transmission lines.

In this paper, we present the results of numerical experiments on the formation of ultrashort pulses of stimulated Raman radiation in a spectral range corresponding to anomalous dispersion of group velocities. It is shown that self-interaction of radiation in glass FL qualitatively changes the nature of the combination conversion of frequency, in particular, stationary pulses with amplitude greatly exceeding the amplitude of pumping pulses can form at the Stokes frequency. In the most interesting case of interaction of the pumping and first Stokes component, propagating in different modes of a two-mode (low-mode) light guide, the starting system of equations for the complex amplitudes of both waves has the form

$$i\frac{\partial\Psi_p}{\partial z} = \frac{\mu_p}{2}\frac{\partial^2\Psi_p}{\partial\tau^2} + \alpha_{pp}\beta|\Psi_p|^2\Psi_p + \alpha_{sp}\beta|\Psi_s|^2\Psi_p - i\frac{\omega_p}{\omega_s}a_{sp}|\Psi_s|^2\Psi_p, \quad (1)$$

$$i\frac{\partial\Psi_s}{\partial z} = \frac{\mu_s}{2}\frac{\partial^2\Psi_s}{\partial\tau^2} + a_{ss}\beta|\Psi_s|^2\Psi_s + \alpha_{sp}\beta|\Psi_p|^2\Psi_s + i\alpha_{sp}|\Psi_p|^2\Psi_s. \quad (2)$$

The variables are normalizxed as follows: $\Psi_+\Psi/|\Psi_{p0}|, \tau=(t-z/v_p])/\tau_{p0}], z=z/z_y, \mu_p=z_a/z_d \mu_c=\mu_p k''_p, \beta=z_y/z_{nl}$, where Ψ_{p0},and τ_{p0} are the initial amplitude and duration of the pumping pulse; $z_y=(g_s|\Psi_{p0}|^2)^{-1}$ is the characteristic amplification length, $z_d=\tau_{p0}^2/k''_{p0}, z_{pnl}=(kn_1|\Psi_{p0}|^2)^{-1}$ are the dispersion and nonlinear lengths; and, (α_{mn}) are the overlap factors for the wave fields of the light-guide modes.[2]

Equations (1) and (2) describe the following physical processes: competition of dispersive spreading and nonliner self-compression of pulses,[5] transfer of frequency modulation of the pumping pulse to the Stokes frequency[3] ("reactive" interaction), and energy exchange between waves ("active" interaction). When stimulated Raman radiation is excited in the region of minimum losses $\lesssim 1$ dB/km ($\lambda = 1.55$) μm, quartz light guide with cross-sectional area $\sim 100\ \mu\text{m}^2$), the characteristic orders of magnitude of the basic parameters of the problem are as follows: for input power ~ 20 W and duration $\tau_{p0} = 5\ ps$, $z_d \sim 10^3$M,$z_y \sim z_{nl} \sim 10^2$M. We note that in a two-mode light guide, the detuning of the group velocities at frequencies ω_s and ω_p can be compensated for by wave-guide dispersion.[4] In view of the low attenuation, it can be ignored, and, then, Eqs. (1) and (2) have the following integral, which expresses the energy-conservation law:

$$P_0 = \int_{-\infty}^{\infty} [\, \Psi_p \Psi_p^* + (\omega_p/\omega_s)\, \Psi_s \Psi_s^* \,]\, d\tau \,. \qquad (3)$$

At the initial stage of evolution of the stimulated Raman radiation, while $|\Psi_s| \ll |\Psi_p|$, Eqs. (1) and (2) can be solved by the method of the inverse problem of scattering theory.[6] A bound state of N solitons is produced from the spectrally restricted pumping pulse (Fig. 1) in the linear regime of the evolution of stimulated Raman radiation. As the intensity of the stimulated Raman radiation is increased, the energy and, therefore, the number of solitons in the pump decrease. The dependence of the distance at which pump solitons exist on the power of illumination signal at the Stokes frequency is illustrated in Fig. 1c. Transfer of frequency modulation of the pump to the Stokes

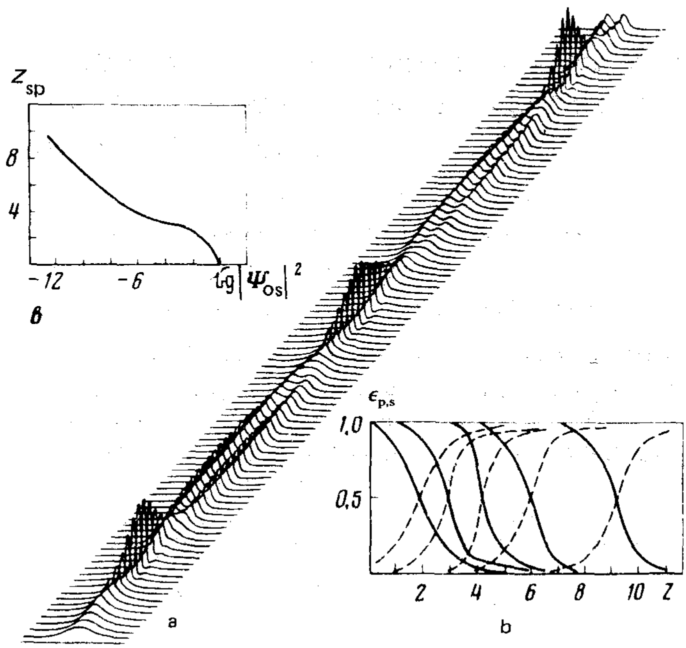

FIG. 1. (a) Bound state of three pump solitons—variation of the temporal envelope as a function of distance; (b) dependence of the normalized pumping energy (solid line) and the signal (dashed line) on the distance for different initial intensities of the stimulated raman emission signal: $|\Psi s0|^2.|\Psi_{p0}|^2 = 4\times 10^{-2}$; 2.5×10^{-3}; 2.5×10^{-8}; 2.5×10^{-9}1 10^{-12}; (c) dependence of the conversion length at half power on key $|\Psi_{s0}|^2$.

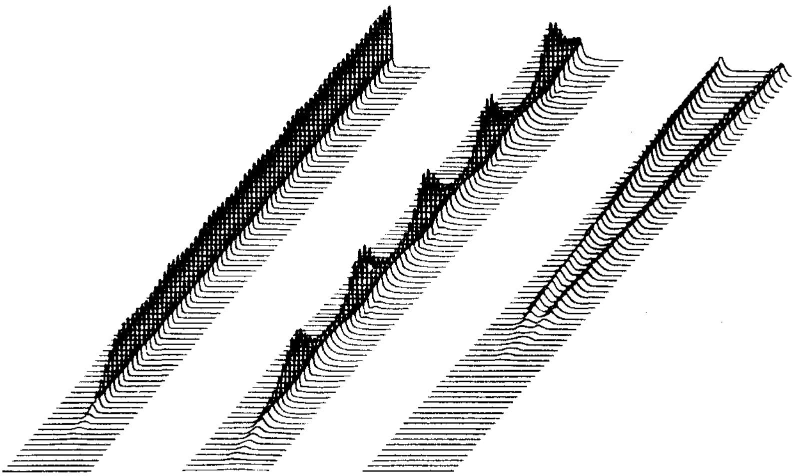

FIG. 2. Spatial-temporal evolution of stimulated Raman radiation pulses (a) Formation of high-energy soliton; (b) formation of a pulse with fluctuating amplitude; (c) creation of diverging pulses.

frequency, predicted in Ref. 3, leads to periodic acceleration (with $\partial\omega_p/\partial t<0$ and retardation ($\partial\omega_p/\partial t>0$) of pulse compression at the Stokes frequency.

In the nonlinear regime of generation of stimulated Raman radiation ($|\Psi_s|\sim|\Psi_p|$), an avalanche-like process of energy transfer to the stokes pulse occurs. Typical results of the numerical solution of Eqs. (1) and (2) are shown in Fig. 2. The transfer of the frequency modulation of the pump to the Stokes frequency (reactive interaction) not only accelerates or retards energy exchange between the waves but also determines the nature of the pulse at the Stokes frequency. If the stimulated Raman radiation pulse is formed at a distance ω_s, corresponding to maximum self-compression of the pumping pulses,[5] then one soliton or a bound state of several solitons forms at the frequency ω_s (Figs. 2a and 2b). If energy transfer occurs in the region of maximum splitting of the pumping pulse, then a pair of dispersing pulses appears at the frequency ω_s (Fig. 2c). In the intermediate range of parameters, pulses that fluctuate in amplitude, which emit energy and are transformed into solitons at distances of the order of tens of dispersion lengths, are formed. We note that the magnitude of the limiting compression can be estimated from the law of conservation of energy (3), assuming that all of the energy of N pump solitons is contained in a single high-energy soliton of stimulated Raman radiation: $\tau_p.\tau_s\simeq(\omega_p/\omega_s)z_d/z_{pnl}$.

The broad Raman scattering lines in quartz glass permit, in principle, the formation of pulses with duration $\tau_{con}\sim100$ fs. To convert the energy of a multisoliton pump pulse into a single-soliton pulse of stimulated Raman radiation, the amplification length z_y must not exceed the characteristic length of maximum self-compression of the pulse z_{ssc}, i.e., $z_y<z_{ssc}$. It follows that to obtain a single soliton pulse with limiting duration ~100 fs, the power of the pumping pulse with duration $\tau_{p0}\simeq5$ ps must exceed 2 kW. In this case, the pumping pulse contains $N=7$ solitons.

Thus the process of stimulated Raman emission in low-mode optical fiber waveguides can be used to transform energy from a bound state of several solitons at the pump frequency to the high-energy single-soliton states at the Stokes frequency. This opens up new possibilities for generating frequency-tunable subpicosecond pulses with controllable parameters.

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