Raman self-frequency shift of the spectrum of femtosecond optical solitons and suppression of this effect in optical fibers and soliton lasers

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A change in the sign of the group-velocity dispersion in a Raman-active nonlinear dispersive medium results in a "quenching" of molecular vibrations. It also effectively suppresses the Raman self-scattering of femtosecond solitons.

A new nonlinear-optics effect was discovered in Refs. 1 and 2: a soliton Raman self-frequency shift. This effect is frequently also called "stimulated soliton Raman self-scattering" to stress the unusual nature of the regime—of a Raman self-frequency shift of a femtosecond pulse whose spectrum spans the band of vibrational resonances of the medium. As a result, the Stokes spectral component of the field, shifted by the frequency of the molecular vibrations, is embodied in the pump pulse itself. The amplification of the low-frequency (Stokes) components in the field of the higher-frequency (anti-Stokes) spectral components of the same soliton pulse leads to a continuous shift of its spectrum. Under typical experimental conditions, the magnitude of this shift is $df/dz = 0.082/\tau_0^4$ THz/km, where τ_0 is the length of the soliton, expressed in picoseconds.[3]

Laboratory prototypes of soliton optical-fiber communication links which have been developed can transmit optical solitons over distances of 10^7 m to 10^9 m at data transmission rates from a few gigabits per second to tens of gigabits per second (see Ref. 4 and the references cited there). This development has focused attention on the problem of suppressing the Raman self-frequency shift (RSFS) of a soliton: This effect is the obstacle to raising data transmission rates into the terabit range, and this effect also limits the length of the pulses which can be generated in femtosecond soliton lasers. So far, only one method for suppressing the RSFS has been proposed in the literature. That method is based on the introduction of a resonant optical loss[5] in the Stokes region in the transmitting medium (an optical fiber).

In the present letter we wish to propose a method for suppressing the RSFS, i.e., the self-scattering of an optical soliton, through a transformation of the phase relations of the frequency components of the soliton in such a way that effective excitation of a molecular-vibration wave is prevented. We will show that the necessary conditions for suppressing RSFS can be arranged in media in which there is a change in sign in the spectrum of the group-velocity dispersion.

Let us examine the propagation of an intense wave packet in a nonlinear Raman-active dispersive medium in the semiclassical approximation of the theory of RSFS:[6,7]

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P_{lin}}{\partial t^2} + \frac{4\pi}{c^2}\frac{\partial^2 P_{Kerr}}{\partial t^2} + \frac{4\pi}{c^2}N\frac{\partial \alpha}{\partial Q}\frac{\partial^2 (QE)}{\partial t^2}, \tag{1}$$

$$\frac{\partial^2 Q}{\partial t^2} + \frac{2}{T_{2Ram}}\frac{\partial Q}{\partial t} + \Omega_R^2 Q = \frac{1}{2m}\frac{\partial \alpha}{\partial Q}n_v E^2, \tag{2}$$

$$\frac{\partial n_v}{\partial t} + \frac{n_v - 1}{T_{1Ram}} = \frac{1}{2\hbar\Omega_R}\frac{\partial \alpha}{\partial Q}E^2\frac{\partial Q}{\partial t}. \tag{3}$$

Equations (1)–(3) are written in terms of standard variables. Here E is the electric field of the light wave, and P_{lin} and P_{Kerr} are respectively the nonresonant linear component and the nonlinear electron (Kerr) component of the polarization of the medium. The molecular (Raman) component of the nonlinear polarization is proportional to the molecular vibration amplitude Q. The dynamics of a wave of stimulated molecular vibrations is found from Eqs. (2) and (3), in which m is the effective mass of the molecules, Ω_R is the resonant Raman frequency, and the time $T_{2\text{Ram}}$ is related to the linewidth of the spontaneous Raman scattering by $T_{2\text{Ram}} = 1/(\pi c \Delta\nu_{\text{Ram}})$. Equation (3) describes the kinetics of the populations n_v of the ground level and the first excited vibrational level of the molecule, and $T_{1\text{Ram}}$ is the relaxation time of a vibrational excitation.

The customary approach in RSFS theory starts from the method of slowly varying amplitudes and the assumption that the spectra of the interacting waves are fairly far apart along the frequency scale and do not overlap. In the problem at hand (of the self-scattering of a femtosecond pulse), however, that approach is incorrect in principle.

In the time-varying case, without a population inversion ($n_v = 1$), the amplitudes of the Fourier components of the nonlinear polarization at the frequency $\omega = \omega_1 + \omega_2 + \omega_3$ can be found from the following expression, according to Eqs. (1) and (2):

$$P_{Ram}(\omega, z) = N\left(\frac{\partial \alpha}{\partial Q}\right)^2 \frac{1}{8\pi^2 m}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{E(\omega_1)E(\omega_2)E(\omega_3)d\omega_1 d\omega_2 e^{i\Delta kz}}{\Omega_R^2 - (\omega_1 + \omega_2)^2 + \frac{2i}{T_{2Ram}}(\omega_1 + \omega_2)}, \tag{4}$$

where $\Delta k = k(\omega) - k(\omega_1) - k(\omega_2) - k(\omega_3)$.

The component of the nonlinear polarization in (4) is determined by a competition between two-photon RSFS processes ($\omega_1 = \omega_1 - \omega_2 + \omega_2$; $\omega_2 = \omega_2 - \omega_1 + \omega_1$) and stimulated four-photon parametric processes ($\omega_a = 2\omega_1 - \omega_2$; $\omega_s = 2\omega_2 - \omega_1$) with $\omega_1 - \omega_2 = \Omega \approx \Omega_R$. It follows from (4) that the two following conditions must hold for an effective resonant excitation of a molecular-vibration wave in the field of one pump pulse containing the spectral components ω_1, ω_2, ω_a, and ω_s:

1. The spectrum of the excited pulse spans the band of vibrational resonances of the medium. Consequently, the length of the exciting pulse must be comparable to the period of the molecular vibrations of the medium.

2. The phases of the spectral components in the pulse must be locked. Out-of-phase spectral components result in a "quenching" of molecular vibrations.

The various spectral components in a pulse are phase-locked when a pulse propagates in the soliton regime in a nonlinear dispersive medium with a negative group-velocity dispersion. In this soliton regime, the dispersive detuning of the phases of the spectral components of the pulse is canceled exactly by nonlinear effects, with the result that the phase of the soliton remains constant for its entire temporal envelope. This phase is a linear function of the length of the medium. In the region of a positive dispersion of the group velocity, in contrast, the phase self-modulation of the light and the dispersion lead to an additional detuning of the phases of the spectral components in the pulse, and the RSFS is effectively suppressed.

One might therefore propose that a method based on a change in the sign of the group-velocity dispersion would be effective for suppressing RSFS. There would be no difficulty in a practical implementation of this method with optical fibers, since the dispersion of the medium could be teamed up with the waveguide dispersion (which results from a change in the profile of the refractive index over the cross section of the fiber) to gain control of the spectrum of the resultant group-velocity dispersion of the fiber.

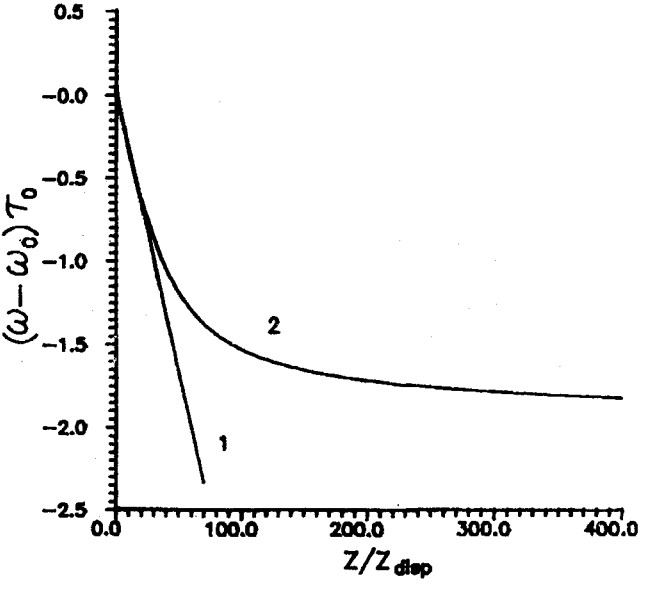

FIG. 1.

The idea of this method is illustrated in Fig. 1 by results calculated for the RSFS of a soliton with a length $\tau_0 = 50$ fs and a wavelength of 1.5 μm in a quartz fiber in which the dispersion of the group velocity changes sign. Shown here is a plot of the central frequency of the spectrum of the optical soliton versus the length of the fiber, for two cases: (1) for a fiber without a change in the sign of the group-velocity dispersion and (2) for a fiber with such a change (the coordinate at which the change in sign occurs is $\omega_{inv} = -2$ for this example). The dimensionless length is expressed in units of the dispersion length $z_{disp} = \tau_0^2/(\partial^2 k/\partial\omega^2)$. A comparison of these two curves clearly illustrates that it is possible to completely suppress the frequency shift of a soliton due to RSFS in a fiber in which the group-velocity dispersion changes sign.

Effects similar to those described above may also occur during the excitation of short pulses in mode-locked fiber lasers. Detailed calculations will be reported in Ref. 8; here we will simply summarize the analysis of the operation of soliton lasers. By using media in which the group-velocity dispersion changes sign in a dispersion spectrum of parabolic shape (this is a good approximation for real fibers with a flattened dispersion), one can effectively suppress the progressive shift of the lasing frequency into the Stokes region. Steady-state mode self-locking can be achieved. The suppression of the RSFS is accompanied by the formation of two coupled optical pulses, one of which propagates in the negative dispersion region, and the other in the positive dispersion region. The two pulses have the same group velocity.

In summary, this analysis demonstrates a fundamentally new possibility for controlling lasing dynamics and the parameters of femtosecond optical solitons in optical fibers in which there is a change in the sign of the group-velocity dispersion.

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