Parametric suppression of stimulated Raman scattering

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The suppression of the stimulated-Raman-scattering gain caused by a parametric interaction has been determined quantitatively for the first time. A good agreement is found between theory and experiment. Single-mode optical fibers, which make it possible to realize a regime of an interaction of plane waves, were used as the stimulated-Raman active media.

The parametric excitation of an anti-Stokes component during stimulated Raman scattering is a fairly well-known effect. There is particular interest in the parametric suppression of stimulated Raman scattering which has been predicted theoretically (Refs. 1 and 2; see the review in Ref. 3 and the bibliography there): Upon a small deviation from phase matching, the stimulated-Raman gain decreases, while under conditions of complete phase matching the gain vanishes (neither the Stokes wave nor the anti-Stokes wave undergoes an exponential amplification). The experiments which have been carried out in bulk media provide only qualitative support for the theory, since the diffractive divergence of the light hinders experiments of this type (see the review[3]). If single-mode optical fibers are used instead, it becomes possible to realize a regime of an interaction of plane waves. The promising outlook for the use of fibers for these purposes was pointed out some time ago.[2]

We describe the electric field of the interacting waves in the single-mode fiber by

$$E=\frac{1}{2}\bar{e}f(r_\perp)\{\widetilde{E}_p(z)\exp(i\omega_p t-ik_p z)+\widetilde{E}_S(z)\exp(i\omega_S t-ik_S z)$$
$$+\widetilde{E}_a(z)\exp(i\omega_a t-ik_a z)\}. \quad (1)$$

Here $E_{p,S,a}$, $\omega_{p,S,a}$, and $k_{p,S,a}$ are the amplitudes, frequencies, and propagation constants of the pump wave, the Stokes-component wave, and the anti-Stokes-component wave; $\bar{e}$ is the polarization unit vector; and $f(r_\perp)$ is the transverse distribution of the field of the mode of the optical waveguide. The following system of equations holds for the amplitudes of the interacting waves under the conditions $|E_{S,a}|^2 \ll |E_p|^2$:

$$\frac{\partial E_p}{\partial z}=-i\frac{2\pi\omega_p^2}{c^2 k_p}(\chi_{NR}^{(3)}+\chi_R^{(3)}(0))I_p E_p \quad (2)$$

$$\frac{\partial E_S}{\partial z}=-i\frac{2\pi\omega_S^2}{c^2 k_S}\{(2\chi_{NR}^{(3)}+\chi_R^{(3)}(0)+\chi_R^{(3)}(\Omega))I_p E_S+(\chi_R^{(3)}(\Omega)$$
$$+\chi_{NR}^{(3)})E_p^2 E_a^*\exp(-i\Delta kz)\}$$

$$\frac{\partial E_a}{\partial z}=-i\frac{2\pi\omega_a^2}{c^2 k_a}\{(2\chi_{NR}^{(3)}+\chi_R^{(3)}(0)+\chi_R^{(3)}(-\Omega))I_p E_a$$
$$+(\chi_R^{(3)}(-\Omega)+\chi_{NR}^{(3)})E_p^2 E_S^*\exp(-i\Delta kz)\},$$

where $\chi_{NR}^{(3)}$ and $\chi_R^{(3)}$ are the nonresonant and resonant cubic nonlinear susceptibilities, $E_{p,S,a}=\sqrt{\alpha}E_{p,S,a}$, $\alpha=\int f^4(r_\perp)d^2(r_\perp)/\int f^2(r_\perp)d^2(r_\perp)\approx 1/2$, $I_p\equiv|E_p|^2$ is the intensity of the pump wave, $\Omega=\omega_p-\omega_S=\omega_a-\omega_p$, and $\Delta k=2k_p-k_S-k_a$. Assuming $\omega_S^2/k_S\approx\omega_a^2/k_a\approx\omega_p^2/k_p=\omega^2/k$, we introduce the coefficient R, which describes the contribution of the electron susceptibility to the nonlinear polarization, $R=\chi_{NR}^{(3)}2\pi\omega^2/(c^2k)$, and we also introduce the complex stimulated-Raman gain $g_0(\Omega)=-i\chi_R^{(3)}(\Omega)4\pi\omega^2/(c^2k)$. It is straightforward to solve system (2) and determine the growth rate of the Stokes wave:

$$E_c \propto \exp(Az)$$
$$A=(RI_p\Delta k+ig_0I_p\Delta k/2-\Delta k^2/4)^{1/2}. \quad (3)$$

In the calculations we used the known[4,5] behavior $g_0(\Omega)$ for quartz glass, with a maximum $\mathrm{Re}(g_0(\Omega))=0.93\times10^{-11}$ cm/W (at the wavelength $\lambda=1.064$ μm), for

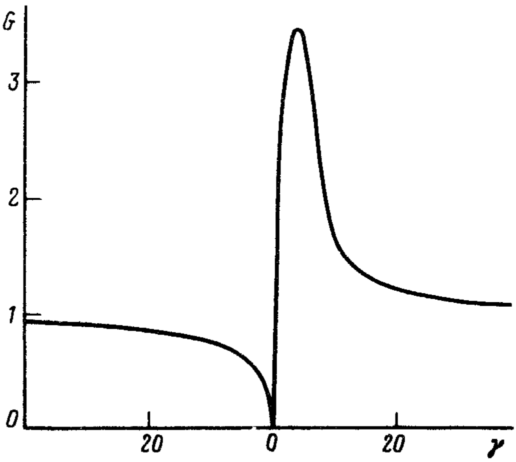

FIG. 1.

$\Omega/(2\pi c) = 440\ \text{cm}^{-1}$. We also used the nonlinear refractive index $N_2 = (\chi_{NR}^{(3)} + \chi_R^{(3)}(0))2\pi\omega^2 n_0/(c^2k^2) = 3.2\times10^{-16}\ \text{cm}^2/\text{W}$. Figure 1 shows the normalized intensity gain for the Stokes wave, $G = g/\text{Re}(g_0(\Omega))$ ($|E_c|^2 \propto \exp(gI_p z)$), versus the parameter $\gamma = \Delta k/(I_p\ \text{Re}(g_0))$ for $\Omega/(2\pi c) = 440\ \text{cm}^{-1}$. The sign of γ is determined by the sign of the dispersion of the waveguide, $d^2k/d\omega^2$, since we have $\Delta k \approx -(d^2k/d\omega^2)\Omega^2$. In the limit $\gamma\to\infty$, the parametric process is ineffective, and the stimulated-Raman gain approaches unity, $G\to1$. In other words, this case corresponds to the "normal" regime of stimulated Raman scattering. In the limit $\gamma\to0$, there is a parametric supression of the exponential growth of the stimulated Raman scattering, and we find $G\to0$. The maximum on the curve of $G(\gamma)$ in the region $\gamma>0$ describes a modulational-instability effect.

Experiments were carried out in the region $d^2k/d\omega^2>0$. For the experiments we selected a polarization-conserving single-mode optical fiber with a strong birefringence (the difference between the effective refractive indices for the axes of the fiber was $\Delta n = 2.3\times10^{-4}$). Since the stimulated-Raman gain depends on the polarization state, the use of polarization-conserving waveguides is a matter of fundamental importance. As pump source we used a cw *QS/ML* Nd:YAG laser ($\lambda = 1.064\ \mu$m, pulse length of 50 ps, power $\leqslant$500 kW). The polarization of the pump light was oriented along the "fast" axis of the fiber. We determined the values of the pump power density I_p which corresponded to the threshold for stimulated Raman scattering, i.e., to the transition of the stimulated Raman scattering to a saturation regime from the spontaneous-noise level in waveguides of various lengths L (from 0.7 m to 10 m). According to Ref. 6, the situation corresponds to the attainment of a stimulated-Raman gain of 16: $g(I_p)I_pL = 16$. We thus determined the $g(I)$ dependence. In addition to the Stokes component of the stimulated Raman scattering [$\Omega/(2\pi c) = 440\ \text{cm}^{-1}$], we observed the anti-Stokes component. The polarizations of the pump, the Stokes component, and the anti-Stokes component were linear and equal to each other. The value of Δk was found from the measured dispersion of the fiber: $d^2k/d\omega^2 = 1.8\times10^{-28}\ \text{s}^2/\text{cm}$ and thus $\Delta k\approx1.24\ \text{cm}^{-1}$. Figure 2 shows experimental points along with a theoretical

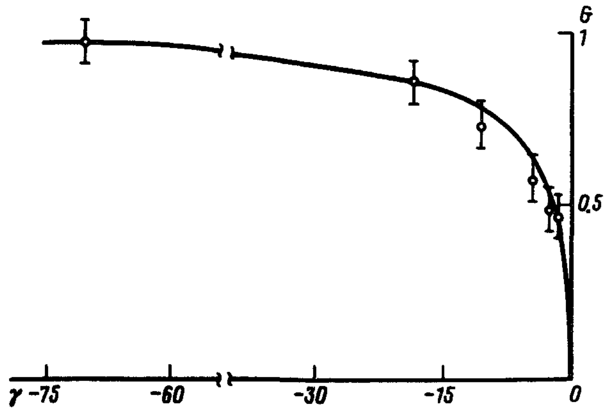

FIG. 2.

curve of $G(\gamma)$. The agreement between theory and experiment is seen to be good.

We also carried out some other experiments on the suppression of stimulated Raman scattering. The degree of spectral broadening of laser pulses due to phase self-modulation at the threshold for stimulated Raman scattering is known[2,7] to be proportional to the ratio of the nonlinear refractive index N_2 to the stimulated-Raman gain. For quartz-glass fibers in the absence of a parametric interaction, the degree of spectral broadening is 33 and is independent of the length of the fiber.[7] In the case of a parametric suppression of stimulated Raman scattering, in contrast, the degree of spectral broadening of the pulses should increase, as we observed experimentally. For a fiber of length $L = 3$ m (in this case we have $\gamma \approx -19$) the degree of broadening was 36, while for $L = 0.7$ m ($\gamma = -2.3$) it was 83.5. These results agree well with the theory.

In summary, we have achieved a more than twofold parametric suppression of the stimulated-Raman gain in a collinear interaction in this study. The degree of suppression of the stimulated Raman scattering could be increased significantly (at the same pump intensities) through the use of fibers with a smaller dispersion. This effect might be utilized to increase the laser-beam power which can be coupled into a fiber without a conversion of the beam energy into stimulated Raman scattering. It might also be utilized to increase the range over which the frequency of ultrashort laser pulses can be scanned and to achieve a corresponding increase in the degree of compression of ultrashort laser pulses in fiber-grating compressors.[7]

[1]S. A. Akhmanov and R. V. Khokhlov, *Problems of Nonlinear Optics*, VINITI, Moscow, 1964.
[2]V. N. Lugovoĭ, Zh. Eksp. Teor. Fiz. **71**, 1307 (1976) [Sov. Phys. JETP **44**, 683 (1976)].
[3]I. R. Shen, *Principles of Nonlinear Optics*, Nauka, Moscow, 1989.
[4]R. Hellwarth *et al.*, Phys. Rev. B **11**, 964 (1975).
[5]R. H. Stolen, in *Optical Fiber Telecommunications* (ed. S. E. Miller and A. G. Chynoweth) Academic, New York, 1979, Ch. 5, p. 125.
[6]R. G. Smith, Appl. Opt. **11**, 2489 (1972).
[7]E. M. Dianov *et al.*, Kvant. Elektron. (Moscow) **15**, 5 (1988) [Sov. J. Quantum Electron. **18**, 1 (1988)].

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