Stimulated Raman scattering with distributed feedback

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It is possible in principle to expand the spectroscopic applications of stimulated Raman scattering. The idea is to excite the medium with two coherent pump beams, which create in the medium a dynamic amplitude-phase grating. This grating causes a scattering with distributed feedback.

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The spectroscopic possibilities of stimulated Raman scattering are known to be limited by the circumstance that the stimulated-Raman spectra contain lines corresponding to a single Raman-active transition (or, in rare cases, a few such transitions).[1] The method of active Raman spectroscopy[2] combines the high efficiency of stimulated Raman scattering with the wide spectroscopic possibilities of spontaneous scattering.

In this letter we show that it is theoretically possible to expand the spectroscopic applications of stimulated Raman scattering by using for excitation coherent pump beams which create in the medium a dynamic amplitude-phase grating. This grating causes a scattering with distributed feedback.[3] We show that the Stokes emission under these conditions has a mode structure characteristic of Bragg diffraction by periodic inhomogeneities in a medium.[4] This effect is not seen in theoretical descriptions of this process which incorporate only the additional parametric contribution to the stimulated Raman scattering.[5,6]

We consider stimulated Raman scattering in a medium bounded by the planes $z = -L/2$ and $z = L/2$. The scattering is excited by two plane monochromatic waves which are propagating in opposite directions at an angle θ from the z axis. They create a standing intensity grating with lines running perpendicular to the z axis. The medium is isotropic. The scattering is caused by an isolated molecular vibration of resonant frequency Ω. The propagation of the Stokes radiation is described by the wave equation for the field,

$$\frac{\partial^2 E}{\partial z^2} - \frac{n^2}{c^2}\frac{\partial^2 E}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P^{NL}}{\partial t^2}, \tag{1}$$

which we seek in the form

$$E_s(z,t) = \frac{1}{2}\exp(i\omega_s t)\,[R(z)\exp(-i\beta_0 z) + S(z)\exp(i\beta_0 z)] + \text{c.c.}, \tag{2}$$

where $\beta_0 = (n\omega_L/c)\cos\theta$, ω_L is the frequency of the exciting light, and ω_s is that of the scattered light. By analogy with active Raman spectroscopy[2] we seek the nonlinear polarization in (1) through the use of the equations of motion for a harmonic oscillator with a driving force $\sim E^2$. It is not difficult to show that in this case P^{NL} is described by

$$P^{NL}_{(z,t)} = \frac{1}{2}\exp(i\omega_s t)\,\frac{\epsilon_0^2 N\left(\frac{\partial\alpha}{\partial Q}\right)_0^2 |E_L^0|^2[(2S+R)e^{i\beta_0 z} + (2R+S)e^{-i\beta_0 z}]}{8m[\Omega^2 - (\omega_L-\omega_s)^2 - i(\omega_L-\omega_s)\Gamma]} + \text{c.c.}, \tag{3}$$

where N is the number of oscillators per unit volume, $|E_L^0|^2$ is the intensity of the exciting light, $(\partial\alpha/\partial Q)_0$ is the Raman polarizability, m is the mass, and Γ is the decay constant. Substitution of (3) and (2) into (1) gives us a system of equations for the amplitudes of the coupled Stokes waves which serves as our starting point:

$$-\frac{\partial R}{\partial z} + [g\alpha''(\delta) - i(\delta + g\alpha'(\delta))]R = \frac{1}{2}ig\alpha(\delta)VS,$$

$$\frac{\partial S}{\partial z} + [g\alpha''(\delta) - i(\delta + g\alpha'(\delta))]S = \frac{1}{2}ig\alpha(\delta)VR, \tag{4}$$

where $\delta \simeq \beta - \beta_0 = n(\omega_s - \omega_0)/c$, g is the gain,[4] $\alpha'(\delta)$ and $\alpha''(\delta)$ are the real and imaginary parts of the normalized Lorentzian line of $\alpha(\delta)$ of the complex cubic nonlinearity, and V is the visibility of the amplitude-phase grating. Using the boundary conditions $R(-L/2) = S(L/2) = 0$, we can write a solution of system (4) in the compact form[3]

$$R = \mathrm{sh}\,[\gamma(z + \frac{1}{2}L)], \qquad S = \pm\,\mathrm{sh}\,[\gamma(z - \frac{1}{2}L)], \tag{5}$$

where the characteristic roots γ are found from

$$\gamma^2 - [g\alpha''(\delta) - i(\delta + g\alpha'(\delta))]^2 = \left(\frac{g\alpha(\delta)V}{2}\right)^2. \tag{6}$$

Substitution of (5) into (4) gives us a system of transcendental equations for the set of eigenvalues γ and the corresponding reduced frequencies δL and excitation thresholds gL:

$$\gamma + [g\alpha''(\delta) - i(\delta + g\alpha'(\delta))] = \pm\, i\frac{g\alpha(\delta)V}{2}e^{\gamma L},$$
$$\gamma - [g\alpha''(\delta) - i(\delta + g\alpha'(\delta))] = \mp\, i\frac{g\alpha(\delta)V}{2}e^{-\gamma L}. \tag{7}$$

Computer solution of system (7) by an iteration method has revealed the mode composition of the scattered light at the threshold for the stimulated Raman scattering (in the linear approximation, without consideration of pump-depletion effects). Figure 1 shows the threshold for the stimulated Raman scattering vs the reduced frequency for the case in which the zeroth Bragg mode coincides with the center of the scattering line, whose reduced half-width is much larger than the distance between modes. It follows from this figure that the amplitude grating for which the zeroth mode has the lowest threshold, $gL = 1.52$, is predominant in this case [since the contribution of $\alpha'(\delta)$ is insignificant at the center of the line]. As in the case of a distributed-feedback laser,[3] the distance between modes is $\Delta\nu \sim L/2$.

Let us examine the possibilities of stimulated Raman scattering under distributed-feedback conditions for the selective excitation of a particular Raman transition. We

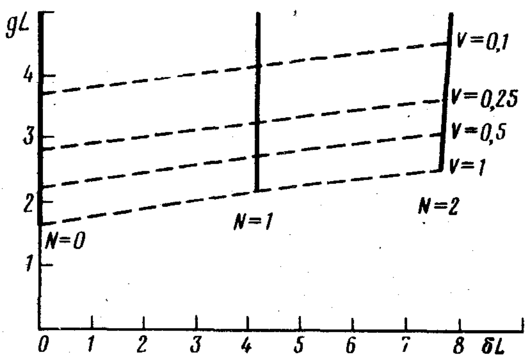

FIG. 1. The reduced threshold for stimulated Raman scattering under distributed-feedback conditions, gL, vs the reduced frequency for various visibilities of the amplitude-phase grating under the condition that the Bragg frequency coincides with the center of the line, whose width is much greater than the distance between modes. Only half of the spectrum is shown, since the spectrum is symmetric with respect to $\delta L = 0$.

assume that the active medium has two Raman lines, ω_1 and ω_2, with gains g_1 and g_2, where $g_1 > g_2$. In the case of ordinary stimulated Raman scattering, the spectrum would reveal a line with a large value of g, because of pump depletion.[1] Let us compare the expression for the threshold for stimulated Raman scattering in the "superluminescence" regime found from the condition for 50% conversion[7] with the expression for the threshold for stimulated Raman scattering under distributed-feedback conditions found for the zeroth Bragg mode, $\omega_0 = \omega_2$, from the solution of system (7). From this comparison we find the ratio of g_1 and g_2 at which the spectrum contains only the line with the smaller value of g:

$$\frac{g_1}{g_2} = \frac{\ln\left(\frac{1}{\mu_0}\right)\sqrt{4-V}}{2\ln(\sqrt{4-V}+2) - \ln V}, \tag{8}$$

where $\mu_0 = (\omega_L/\omega_s)(|E_s^0|^2/|E_L^0|^2)$, and $|E_s^0|^2$ is the intensity of the "seed" at the Stokes frequency. It follows from (8) that in order to increase the "suppression" of the strong line during stimulated Raman scattering under distributed-feedback conditions it is necessary to record an amplitude-phase grating of maximum visibility at the maximum values of $|E_L|^2$. Working from (8), we can estimate the maximum value of g_1/g_2, which turns out to be ~ 20 for the typical values of μ_0 for stimulated Raman scattering[7] and for a visibility $V = 1$.

The results derived here regarding stimulated Raman scattering under distributed-feedback conditions raise the hope that the effect will find at least two applications: for producing tunable narrow-band emission[8] and for expanding the spectroscopic possibilities of stimulated Raman scattering without the use of tunable lasers.

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[1]M. M. Sushchinskiĭ, Spektry kombinatsionnogo rasseyaniya molekul i kristallov (Raman Spectra of Molecules and Crystals), Nauka, Moscow, 1969.
[2]S. A. Akhmanov and K. I. Koroteev, Metody nelineĭnoĭ optiki v spektroskopii rasseyaniya sveta (Methods of Nonlinear Optics in Light-Scattering Spectroscopy), Nauka, Moscow, 1981.
[3]H. Kogelnik and C. V. Shank, J. Appl. Phys. **43**, 2328 (1972).
[4]A. Yariv, Quantum Electronics, Wiley, New York (1975) (Russ. transl. Sov. radio, Moscow, 1980).
[5]O. M. Vokhnik and V. I. Odintsov, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 407 (1979) [Sov. Tech. Phys. Lett. **5**, 164 (1979)].
[6]V. M. Izgorodin, S. B. Kormer, G. G. Kochemasov, V. D. Nikolaev, and A. V. Pinegin, Kvant. Elektron. (Moscow) **9**, 229 (1982) [Sov. J. Quantum Electron. **12**, 119 (1982)].
[7]S. A. Akhmanov, Yu. E. D'yakov, and A. S. Chirkin, Vvedenie v statisticheskuyu radiofiziku i optiku (Introduction to Statistical Radiophysics and Optics), Nauka, Moscow, 1981.
[8]S. A. Akhmanov and G. A. Lyakhov, Zh. Eksp. Teor. Fiz. **66**, 96 (1974).

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