Possibility of effective generation by a Raman laser with broadband excitation

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We discuss the dependence of the efficiency of amplification and generation of the Stokes component of stimulated Raman scattering (SRS) on the ratio of the spectral widths of the pump and of the spontaneous Raman scattering. It is shown that with suitable choice of the pump-resonator length it is possible to obtain effective lasing with broadband excitation. A new interpretation is proposed for the available experimental results.

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It was experimentally observed in[1] that at a sufficiently high pump-radiation intensity the efficiency of Raman amplification does not depend on the ratio of the spectral widths $\Delta\nu_p$ of the pump and $\Delta\nu_\Lambda$ of the spontaneous Raman scattering. This gave grounds for expecting the efficiency of Raman lasers to be likewise independent of the ratio $\Delta\nu_p/\Delta\nu_\Lambda$. Nonetheless, experiments[2,3] have shown that in the case of narrow-band excitation ($\Delta\nu_p \ll \Delta\nu_\Lambda$) the lasing efficiency is much higher than for broad-band excitation ($\Delta\nu_p \gg \Delta\nu_\Lambda$). This was explained in[4] under the assumption that the pumping is a Gaussian random process. We show in this paper that if certain conditions that are quite simple to realize in experiment are satisfied, it is possible to obtain effective lasing with broadband excitation.

We consider a one-dimensional traveling-wave Raman laser with a ring resonator completely filled with a nondispersive active medium of length l, made up of mirrors that are transparent to the pump frequency. The equations for the complex amplitudes A_0 and A_1 of the pump and of the Stokes radiation and for the off-diagonal matrix element of the density σ are well known[5]:

$$\frac{1}{v}\frac{\partial A_0}{\partial t} + \frac{\partial A_0}{\partial z} = -\gamma_0 \sigma^* A_1, \qquad \frac{1}{v}\frac{\partial A_1}{\partial t} + \frac{\partial A_1}{\partial z} = \gamma_1 \sigma A_0,$$

$$\frac{\partial \sigma}{\partial t} + \frac{1}{T}\sigma = \gamma_\sigma A_0^* A_1, \tag{1}$$

where γ_0, γ_1, γ_σ, and T are the interaction and relaxation constants. The system (1) is considered with the boundary conditions

$$A_0(t, 0) = A_0^\circ(t), \qquad A_1(t, 0) = \sqrt{r} A_1(t, l), \tag{2}$$

where r is the reflection coefficient of the exit mirror and $A_0^0(t)$ is a specified function.

Assume that the function $A_0^0(t)$ is periodic with a period $T_0 = l/v$, and satisfies the condition

$$\left[\frac{1}{T_0}\int_0^{T_0} |A_0^\circ|^4 dt - \left(\frac{1}{T_0}\int_0^{T_0} |A_0^\circ|^2 dt\right)^2\right]\left(\frac{1}{T_0}\int_0^{T_0} |A_0^\circ|^4 dt\right)^{-1} << 1, \tag{3}$$

i.e., the spectral width of the pump is connected mainly with the phase modulation. The solution of the problem (1), (2) then takes the form

$$A_0(t, z) = \tilde{A}_0(z) A_0^\circ(\eta), \quad A_1(t, z) = \tilde{A}_1(z) A_0^\circ(\eta). \tag{4}$$

Here $\eta = t - z/v$ and the functions A_0 and A_1 are positive and satisfy the equations

$$\frac{d\tilde{A}_0^2}{dz} = -a_0 \tilde{A}_0^2 \tilde{A}_1^2, \qquad \frac{d\tilde{A}_1^2}{dz} = a_1 \tilde{A}_1^2 \tilde{A}_0^2, \tag{5}$$

where

$$a_i = 2\gamma_i \gamma_\sigma T I_0, \quad I_0 = \frac{1}{T_0}\int_0^{T_0} |A_0^\circ|^2 dt,$$

and the conditions

$$\tilde{A}_0(0) = 1, \qquad \tilde{A}_1(0) = \sqrt{r}\tilde{A}_1(l). \tag{6}$$

It is seen from (4) and (5) that in this case the lasing efficiency is determined by the pump intensity averaged over the period, and does not depend on the width of the spectrum or on other spectral characteristics. If the condition (3) is not satisfied, then the representation of the type (4)–(6) is valid at not too large excesses above the lasing threshold. With respect to Eqs. (5), we note that they have been thoroughly investigated in connection with Raman amplification,[6] and we shall not dwell on the analysis of their solutions.

We now discuss the causes of the described effect and the possible methods of its utilization. An analysis of Eqs. (1) shows that the efficiency of the amplification of the Stokes radiation is determined by the character of the temporal variation of the input amplitudes of the corresponding fields, a particularly significant factor in broadband excitation. In this case, if the temporal behavior of the input amplitudes of the pump and of the Stokes component is similar, i.e., the relation

$$A_1(t, 0) \sim A_0(t, 0) \tag{7}$$

is satisfied, then the gain increment is maximal, does not depend on $\Delta\nu_p$, and coincides practically (exactly in the case of phase-modulated pumping) with the gain growth rate for monochromatic pumping of the same intensity. On the other hand, if (7) is not satisfied, then the gain growth rate is much smaller and does not exceed a value proportional to $(\Delta\nu_p)^{-1}$.[4] In experiments of the type performed in[1], where the Stokes signal develops from noise, the gain efficiency at sufficient pump intensity (which is connected with the presence of dispersion of the active medium) is therefore independent of the ratio $\Delta\nu_p/\Delta\nu_\Lambda$, inasmuch as the noise of spontaneous Raman scattering always contains Stokes radiation that satisfies the condition (7). In Raman lasers, however, the lasing efficiency under broadband excitation is in the general case low, since the Stokes signal, while satisfying the condition (7) during a certain pass through the resonator and increasing considerably, no longer satisfies this condition during the next pass, and will in essence not be amplified. An important exception is the here-discussed case of periodic pumping with a period T_0, under which the similarity condition (7) is satisfied all the time. We note that the described results do not contradict[4], since the discussed pumping is outside the framework of the assumptions made in[4]. Understandably, effective lasing is ensured by satisfaction of (7) during a time $\tau > \tau_g$, where τ_g is the generation buildup time. This means that the generation will be effective if the input pump amplitude is of the form

$$A_0^\circ(t) = f_1(t)\tilde{A}_0^\circ(t), \tag{8}$$

where $\tilde{A}_0^0(t)$ is periodic over a time interval $\sim \tau_g$, and $f_1(t)$ changes little during the period T_0. The representation (8) is valid for pump-laser emission at an effective resonator length $l_1 = l/k, k = 1, 2, \cdots$.[7] By the same token, the task of obtaining effective lasing in a Raman laser with a dispersionless active medium, under broadband excitation, reduces to matching of the lengths of the pump-laser resonators and the Stokes radiation. If a traveling wave is also generated in the pump laser, then the permissible length mismatches are given by

$$\Delta l \lesssim l\,(k\tau_g\, v\Delta\nu_p)^{-1}. \tag{9}$$

Assuming $\tau_g \sim l[v(1-r)]^{-1}$, $r \ll 1$, and $k = 1$, we find from (9) that $\Delta l \leqslant (\Delta\nu_p)^{-1}$. We see therefore that the effect under discussion is quite simple to realize at spectral widths $\Delta\nu_p \lesssim 1 - 5$ cm^{-1}. To observe the effect in the case of dispersive active media it obviously suffices, when the lengths are matched, to use in the Raman laser a resonator with an effective length satisfying the condition

$$l \ll v_0 [| v_0 - v_1 | \Delta\nu_p]^{-1} , \qquad (10)$$

where v_0 and v_1 are the group velocities of the pump waves and of the Stokes component. We indicate, finally, that for a plane-parallel resonator that is completely or partially filled, the foregoing considerations remain in force, and it is only necessary to introduce the corresponding changes in the value of the effective length.

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