Stimulated Raman scattering of light by surface polaritons

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We demonstrate theoretically the possibility, in principle, of stimulated Raman scattering of light by surface polaritons, and obtain an explicit expression for the amplification coefficient of the process.

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The physical properties of surface polaritons (SP) have been intensively investigated in recent years.[1–7] Two fundamental experimental methods are used for this purpose: the method of attenuated total internal reflection (ATIR) and the method of spontaneous Raman scattering (SRS) of light. We wish to point out the feasibility of using a new phenomenon with SP participated, namely stimulated scattering (SRS) of light by SP.

To this end, we solved the problem of stationary parametric amplification of the Stokes and SP waves, which are connected with the quadratic nonlinearity of the medium in a field of a given pump wave. The concrete formulation of the problem consists in the following. In the region $z > 0$ (see Fig. 1) is located a nonlinear cubic crystal, with which the SP is genetically connected. The medium in the region $z < 0$ is linear and transparent. The dielectric constants in the polariton region will be designated by $\epsilon(\omega) = \epsilon'(\omega) + i\epsilon''(\omega)$ and ϵ_1 respectively. Let all three interaction waves propagate in the same direction—

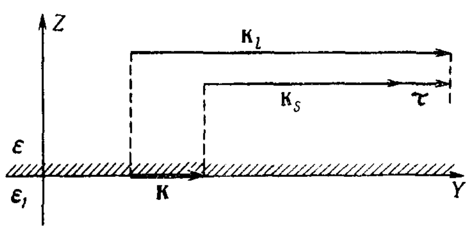

FIG. 1.

along the Y axis. We assume the pump to be a plane monochromatic wave and represent its field in the region $z>0$ in the form $\mathbf{E}_l(\mathbf{r},t)=\mathbf{e}_l A_l \exp[i(k_l y-\omega_l t)]$ + c. c. Here and below $\mathbf{e}$ are the unit vectors of the wave polarization, A are scalar amplitudes, $\mathbf{k}$ are the wave vectors, ω are the frequencies $(\omega_l=\omega_s+\omega_p)$, the indices l,s, and p correspond throughout to the pump, Stokes, and SP waves, respectively. There is no absorption at the frequencies $\omega_{l,s}$.

We seek the SP field $\mathbf{E}_p(\mathbf{r},t)=\mathbf{E}(\mathbf{r})e^{-i\omega_p t}$ + c. c. in the form

$$\mathbf{E}(\mathbf{r}) = \begin{cases} \mathbf{e}A(y)\exp(i\mathbf{Q}\mathbf{r}), & z>0 \\ \mathbf{e}_1 A_1(y)\exp(i\vec{\mathscr{P}}\mathbf{r}) & z<0, \end{cases} \tag{1}$$

where

$$\mathbf{Q}=(0,k,is), \qquad \mathbf{e}=(0,is,-k)/\sigma, \qquad \sigma=(k^2+s^2)^{1/2};$$

$$\vec{\mathscr{P}}=(0,k,-ip), \qquad \mathbf{e}_1=(0,ip,k)/\sigma_1, \qquad \sigma_1=(k^2+p^2)^{1/2};$$

$$k=q\sqrt{\frac{\tilde{\epsilon}\epsilon_1}{\tilde{\epsilon}+\epsilon_1}}, \quad s=q\sqrt{-\frac{\tilde{\epsilon}^2}{\tilde{\epsilon}+\epsilon_1}}, \quad p=q\sqrt{-\frac{\epsilon_1^2}{\tilde{\epsilon}+\epsilon_1}},$$

$$q=\frac{\omega_p}{c},$$

$\tilde{\epsilon}$ is the value of ϵ without allowance for the dissipation processes. The quantities A and A_1 are connected by the boundary condition $s\sigma_1 A=p\sigma A_1$. Expression (1) agree with those for the SP in a linear medium,[4] except that the amplitudes A and A_1 depend on Y.

We seek the Stokes wave in the region $z>0$ in the form

$$\mathbf{E}_s(\mathbf{r},t)=\mathbf{e}_s A_s(y)\exp[i(k_s y-\omega_s t)-sz]+\text{c.c.}, \qquad k_s=q_s\sqrt{\epsilon_s},$$

$$q_s=\omega_s/c, \quad \mathbf{e}_s\perp Y$$

(the polarizations of the interacting waves $\omega_{l,s}$ are assumed to be linear and fixed).

The parametric interaction of the waves takes place in a layer of thickness $\sim s^{-1}$ in the region $z>0$. This thickness greatly exceeds the wavelength of the Stokes radiation $(s^{-1}\gg k_s^{-1})$ [1)], so that we can neglect the distortions of the Stokes field in the region $z>0$, due to the interface, as well as the penetration of this field into the region $z<0$.

The interaction of the waves is due to the quadratic nonlinearity of the polarization $\mathbf{P}_{s,p}^{NL}$ are the frequencies $\omega_{s,p}$ in the region $z>0$. What we need in fact are the components $P_p^{NL}=\mathbf{e}^*\mathbf{P}_p^{NL}$ and $P_s^{NL}=\mathbf{e}_s\mathbf{P}_s^{NL}$, which are given by the following:

$$P_p^{NL}=\chi A_l A_s^*\exp[i(k_l-k_s)y-i\omega_p t]+\text{c.c.},$$

$$P_s^{NL}=\chi A_l A^*\exp[i(k_l-k)y-sz-i\omega_s t]+\text{c.c.}$$

Here $\chi=\Sigma_{ijk}e_i^* e_{lj} e_{sk}\chi_{ijk}(\omega_l-\omega_s)$, and χ_{ijk} is the quadratic nonlinear polarizability of the medium[8] in the region $z>0$.

The amplitudes A and A_s satisfy the usual abbreviated equations, which are obtained from Maxwell's equations within the framework of the known procedure.[8] We seek their solutions in the form

$$A(y) = a\exp[(i\,\tau/2 + \kappa)y], \quad A_s(y) = a_s\exp[(i\,\tau/2 + \kappa^*)y], \quad \tau = k_l - k_s - k, \qquad (2)$$

assuming the quantities a, a_s, and κ to be independent of Y. The quantity τ is the wave detuning, and the parameter κ determines in final analysis the gain $g = 2\,\mathrm{Re}\kappa$.

Substituting (2) in the abbreviated equations and assuming that at polariton frequencies, as usual,[9] the absorption is large and $|\kappa| \ll \alpha$, where $\alpha = q^2\epsilon''\sigma^2/k^3$, we obtain

$$a = \frac{4\pi q^2 \chi \sigma^2 A_l a_s^*}{k^3(\tau - ia)}, \qquad a_s = \frac{4\pi q_s^2 \chi A_l a^*}{k_s(\tau - 2i\kappa^*) - s^2(1 - e_{sz}^2)}.$$

From the condition that these equations be compatible we obtain κ and then

$$g = \frac{g_0}{1 + (\tau/a)^2}, \qquad g_0 = \frac{16\pi^2 q_s^2 |\chi A_l|^2}{k_s \epsilon''}.$$

The quantity g_0 coincides formally with the gain at the line center of SRS by a hypothetical volume polariton of frequency ω_p (actually the region of the existence of SP is forbidden for the dispersion branches of volume polaritons). The line shape for the gain is given by the factor $[1 + (\tau/\alpha)^2]^{-1}$. The line center corresponds to $\tau = 0$, i.e., it lies on the SP dispersion branch obtained without allowance for absorption. Representing τ within the limits of the scattering line in the form $\tau \approx \tau'(\omega_s - \omega_s^0)$, where $\tau' = \partial\tau(\omega_s^0)/\partial\omega_s = V_p^{-1} - V_s^{-1}$, ω_s^0 is the line-center frequency, and $V_{s,p}$ are the group velocities of the SP and of the Stokes waves at $\omega_s = \omega_s^0$, we conclude that the line has an approximate Lorentz shape with half-width $2\alpha/|\tau'|$.

The results indicated that SRS of light by SP is perfectly feasible at pump powers of the same order as in the case of volume polaritons.[10,11] To be sure, in the case of SP the transverse aperture in the direction of the Z axis ($\sim s^{-1}$), and accordingly the Stokes-wave intensity integrated over the cross section, is much smaller, but this difficulty can be overcome. This phenomenon, which is of interest and of importance from the physical point of view, can be used, in particular, to tune the emission frequency in integrated-optics systems.

1) If $\omega_s \gg \omega_p$, as is usually the case.

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