STIMULATED RAMAN SCATTERING IN A RANDOMLY INHOMOGENEOUS MEDIUM

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The problem on stimulated Raman scattering (SRS) in a randomly inhomogeneous medium is considered using numerical simulation techniques. Scattering by the fluctuations in the refractive index in the randomly inhomogeneous medium is shown to have a significant effect on SRS for both a fixed pump field and pump beam exhaustion. For laser radiation at 1.06 μm *propagating through a turbulent atmosphere this effect can be significant even on paths of several hundreds of meters in length.*

When an intense laser beam propagates through the atmosphere, stimulated Raman scattering (SRS) can appear.[1] In addition, SRS affects strongly the beam depending on the radiation intensity, the wavelength, etc. on paths whose length vary from several hundreds of meters to several tens of kilometers. As is well known, the random fluctuations in the dielectric constant due to the turbulent air motion strongly affect the laser beam. Therefore, the problem of stimulated Raman scattering in a randomly inhomogeneous medium is of interest for estimating the contribution of SRS to the propagation of intense laser beams. In the paper this problem is studied by the methods of numerical simulation for stationary SRS of the Gaussian pump beams.

Let us assume that the Gaussian pump beam with the intensity $I = I_0\, e^{-(r/a)^2}$, where a is the characteristic beam radius, is incident on the boundary of the randomly inhomogeneous medium. Equations of quasioptics for the complex amplitudes of pump waves E_p and Stokes component E_S with allowance for SRS in the randomly inhomogeneous medium take the form

$$\left(2\,i\,\kappa_p \frac{\partial}{\partial z} + \Delta_\perp + \kappa_p^2 \frac{2\tilde{n}}{n_0}\right) E_p = -\,i\kappa_p\, g\, \frac{\omega_p}{\omega_S}\, |E_S|^2 E_p\,, \qquad (1)$$

$$\left(2\,i\,\kappa_S \frac{\partial}{\partial z} + \Delta_\perp + \kappa_S^2 \frac{2\tilde{n}}{n_0}\right) E_S = -\,i\,\kappa_S\, g\; |E_p|^2 E_S\,, \qquad (2)$$

where ω_p and κ_p are the frequency and the wave number of the pumping radiation and ω_S and κ_S are the same ones for the Stokes component, $\tilde{n}$ is the random component of the refractive index $n = n_0 + \tilde{n}$ engendered by the turbulent fluctuations of the parameters of the medium, g is the coefficient of amplification due to stimulated Raman scattering, and $\Delta_\perp$ is the transverse Laplacian operator.

The complex amplitude of the Stokes radiation on the boundary of the randomly inhomogeneous medium is specified in the form of the random field δ–correlated over the transverse coordinate and caused by spontaneous Raman scattering and fluctuations of the Stokes field on the boundary.[2]

Equations (1) and (2) were solved by the separation technique for physical factors.[4] In so doing, the randomly inhomogeneous medium was represented by the sequence of random phase screens.[3,4] For the fixed sequence of the random phase screens we calculated the physical quantities of interest for us (pump and Stokes radiation intensities and powers) and averaged them over an ensemble of realizations of the random Stokes seed upon entering the medium. Because the characteristic relaxation time for the refractive index field due to the turbulence is much longer than the transverse relaxation time T of the active Raman transitions and of the duration of laser pulses for which SRS can be obtained at present, the above–mentioned averaging is equivalent to the averaging over the time interval much shorter than the relaxation time for the refractive index field, but much longer than T, or to averaging over the time over which the pulse acts.

As a result of such an averaging, one realization of the corresponding random quantity was obtained. This realization was determined by the real realization of the random field of the refractive index (by the specific collection of the random phase screens). By performing such calculations for different collections of random phase screens, we obtained different realizations of the quantities of interest for us, which were further used to determine the statistical properties of these quantities. In the calculations the refractive index fluctuations were chosen with the von Karman spectrum

$$\Phi_n(\kappa) = 0.033 C_n^2 (\kappa^2 + \kappa_0^2)^{-11/6} \exp(-\kappa^2/\kappa_m^2)\,, \qquad (3)$$

where $\kappa_0 = 2\pi/L_0$, L_0 is the outer scale of the turbulence, $\kappa_m = 2\pi/l_0$, l_0 is the inner scale of the turbulence, and C_n^2 is the structure characteristic of the refractive index fluctuations.

Calculations were performed for the inner scale of turbulence l_0= 0.9 cm, the characteristic radius of the beam a = 5 cm, and the radiation wavelength λ = 1.06 μm. The amplification coefficient due to SRS was $g = 2.5\cdot10^{-12}$ cm/W. The structure characteristic of the refractive index fluctuations C_n^2 varied from 10^{-17} to 10^{-14} cm$^{-2/3}$. These values are most typical of the surface atmospheric layer.

Figure 1*a* shows the plots of the dependence of the average power for the Stokes beam P_S and pump beam P_p on the longitudinal coordinate z for different values of the structure characteristic of the refractive index fluctuations C_n^2. The pump power upon entering the medium was $P_0 = 10^9$ W. The power P_S is shown in the figure in both linear and logarithmic scales. As can be seen from Fig. 1*a*, the strong dependence of the Stokes beam power on C_n^2 is observed both in the region in which SRS occurs in the fixed pump field ($P_S \ll P_p$) and in the region in which the pump beam is exhausted. In addition the power of the Stokes component is increased with increase of C_n^2 for any longitudinal coordinate. Such a dependence on C_n^2 is observed in the case in which the decrease of the average intensity of the pump beam due to scattering by turbulent fluctuations of the refractive index is negligible at the distance at which a considerable portion of the energy is transferred into the Stokes beam.

In Fig. 1*b* the dependences of P_S on z for different C_n^2 are shown in the case in which the above condition may be violated. On the initial section of the path, where the pump intensity varies insignificantly, the dependence is the same as in the previous case: the value of P_S increases with increase of C_n^2. At the same time, the sharp decrease of the rate of growth for the Stokes power due to the decrease of the pump intensity takes place for large values of C_n^2 ($C_n^2 = 10^{-14}$ cm$^{-2/3}$), and the Stokes power P_S for $C_n^2 = 10^{-14}$ cm$^{-2/3}$ becomes smaller than that for $C_n^2 = 10^{-15}$ cm$^{-2/3}$ at a certain distance from the starting point of the path.

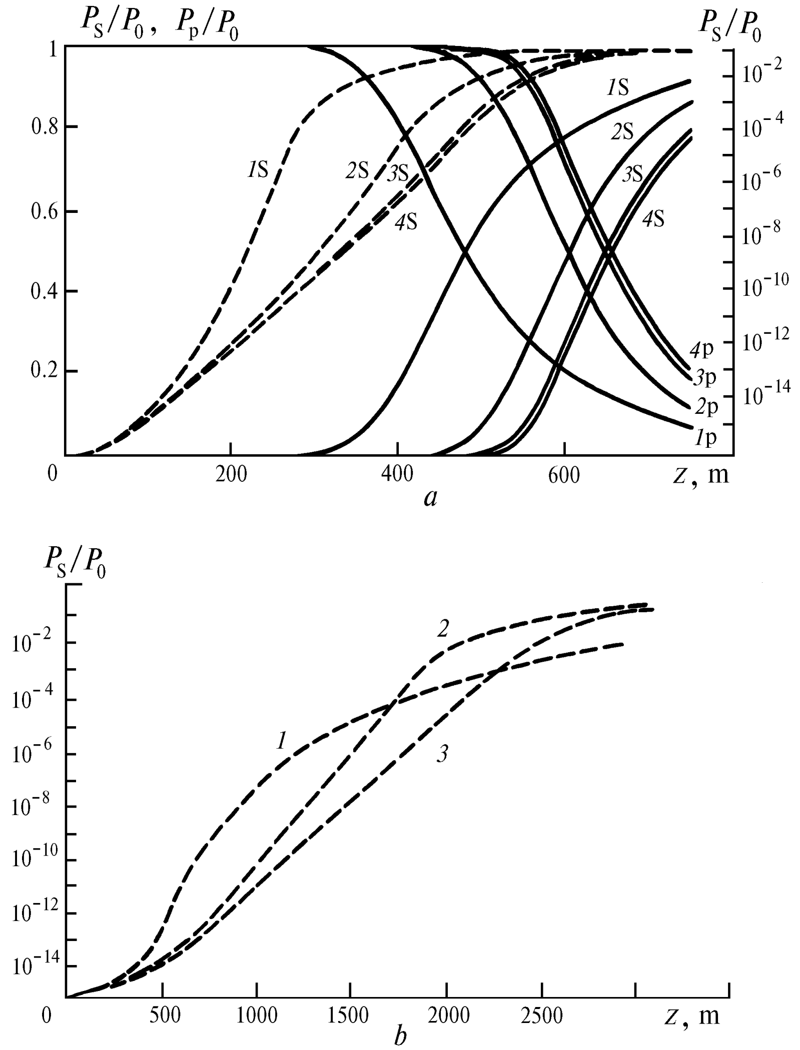


FIG. 1. Dependence of the average power of the pump beam P_p (curves denoted by p) and Stokes beam P_S (denoted by S) on the longitudinal coordinate z for different values of C_n^2 in linear (solid lines) and logarithmic (dashed lines) scales (a): 1) $C_n^2 = 10^{-14}$, 2) 10^{-15}, 3) 10^{-16}, and 4) 10^{-18} cm$^{-2/3}$. Dependence of the average power of the Stokes beam P_S on the longitudinal coordinate z for different values of C_n^2 for $P_0 = 2.5\cdot10^8$ W (b): 1) $C_n^2 = 10^{-14}$, 2) 10^{-15}, and 3) 10^{-16} cm$^{-2/3}$.

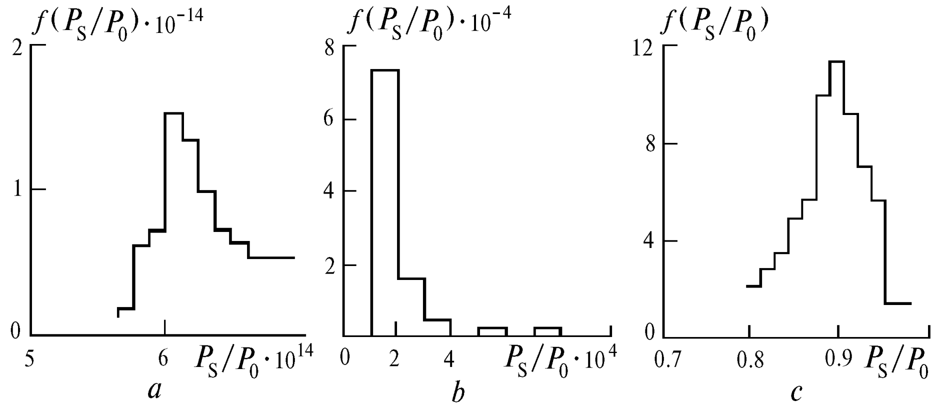
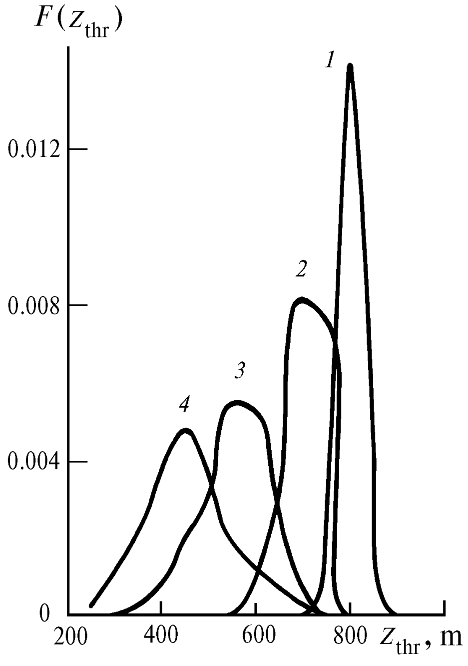


FIG. 2. Distribution functions for the energy of the Stokes beam P_S for different longitudinal coordinate z: a) 125, *b)* 375, *and c)* 750 m.



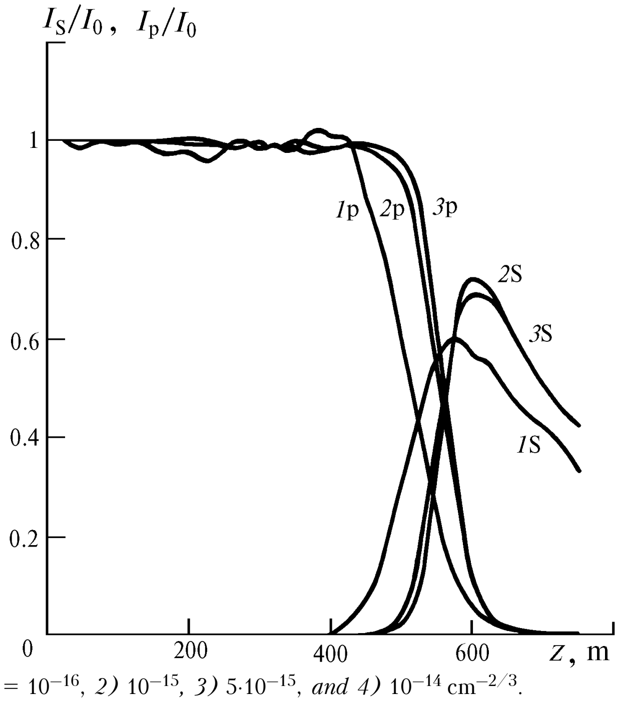


FIG. 3. The distribution functions for the value z_{thr}: 1) C_n^2 = 10^{-16}, *2)* 10^{-15}, *3)* $5\cdot10^{-15}$, *and 4)* 10^{-14} cm$^{-2/3}$.

FIG. 4. Dependence of the average pump intensity I_p (curves denoted by p) and Stokes radiation (denoted by S) on the beam axis on the longitudinal coordinate z at different values of C_n^2: 1) 10^{-14}, *2)* 10^{-15}, *and 3)* 10^{-16} cm$^{-2/3}$.

In Fig. 2 the distribution functions $f(P_S)$ of the random quantity P_S are shown for $P_0 = 10^9$ W, $C_n^2 = 10^{-15}$ cm$^{-2/3}$, and different longitudinal coordinate ($\int f(P_S)\,dP_S = 1$). As can be seen, the average value of P_S and its variance as well as the form of the distribution function vary with increase of z. On the initial section of the path the most probable value of P_S is of the same order of magnitude as the square root of the variance, or much greater. Then the distribution function sharply decays at $P_S = 0$, the most probable value of P_S is smaller than the square root of the variance $(\sigma_{pS})^{1/2}$, and when the energy transfers into the Stokes beam, the distribution function has the same form as on the initial section of the path.

The calculations performed for $P_0 = 10^9$ W and different values of C_n^2 varying from 10^{-17} to 10^{-14} cm$^{-2/3}$ showed that this behavior of the distribution function retains for any C_n^2.

It is convenient to introduce the parameter z_{thr} that means the path length at which the significant portion of the beam energy (according to our calculations, about 1%) is transferred into the Stokes component and to estimate the minimum length of the path for which SRS may significantly contribute to the propagation of the intense laser beam.

Figure 3 shows the distribution functions $F(z_{thr})$ of this random quantity with a pump power of 10^9 W for different values of C_n^2 ($\int F(z_{thr})\,dz_{thr} = 1$). As can be seen, the average value of $z_{\rm thr}$ decreases and the variance increases with increase of C_n^2. But there are no considerable changes in the form of the distribution function.

Calculations show that the Stokes intensity $I_{\rm S}$ on the axis is dependent on C_n^2 both in the regime of the fixed pump field and in the regime of the pump beam exhaustion (see Fig. 4). The distribution function for the Stokes intensity undergoes the same qualitative changes as the distribution function for the Stokes power. The sharp decrease of the Stokes intensity on the axis in the region where $I_{\rm S} > I_{\rm p}$ is due to the large divergence of the Stokes beam obtained as a result of SRS.

The effect of SRS in the direction of beam propagation on the beam of the intense laser radiation is reduced to the energy transfer into the Stokes component. Under these conditions the beam divergence is increased. The increase of the beam divergence also takes place as a result of propagation of the laser beam through the randomly inhomogeneous medium. Therefore, the problem of interest is how SRS affects the beam pattern in the randomly inhomogeneous medium. In order to elucidate this problem, we performed the calculations for three cases: (1) $C_n^2 = 0$ and $P_l = 2.5\cdot10^9$ W, (2) $C_n^2 = 10^{-14}$ cm$^{-2/3}$ and $P_l = 10^7$ W, and (3) $C_n^2 = 10^{-14}$ cm$^{-2/3}$ and $P_l = 2.5\cdot10^9$ W. In the first and third cases we calculated the parameter $K = P_{\rm por}/P$ specifying the portion of the beam power propagating at the fixed angle $\vartheta = 4\,\kappa_l\,a$ at the distance from the starting point of the path sufficient for the complete transfer of the energy into the Stokes beam. The first case corresponded to SRS in the homogeneous medium. The parameter $K = 0.2$ was determined by SRS alone. In the second case SRS had no pronounced effect on the beam. The parameter $K = 0.2$ was determined only by scattering in the randomly inhomogeneous medium. In the third case both SRS and randomly inhomogeneous medium had pronounced effects. In this case $K = 0.04$. Thus, in the case in which both SRS and scattering in the randomly inhomogeneous medium had pronounced effects, these two effects interacted.

Our results show that fluctuations in the refractive index of the medium due to the turbulence may contribute to the SRS process and to the propagation of the intense laser beam in the atmosphere under conditions of SRS. In this case the contribution can be significant even on paths of several hundreds of meters in length.

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