STIMULATED RAMAN SCATTERING OF A FOCUSED PULSED LASER BEAM IN THE ATMOSPHERE

M.F. Shalyaev and V.P. Sadovnikov

Institute of Radioelectronics, Academy of Sciences of the USSR, Moscow

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A theoretical investigation of stimulated Raman scattering (SRS) of short pulses of laser radiation focused in the atmosphere is discussed. The beam focusing makes the stimulated Raman effect stronger and localizes the zone of its greatest efficiency within the beam caustic that can be useful for some practical applications. It is shown that an account of the effect of the SRS on the atmospheric nitrogen could be of practical importance in some lidar applications.

The problem of a reliable account for stimulated Raman scattering (SRS) is particularly important in the analysis of the transfer of high–power laser beams through the atmosphere[1] as well as in laser sounding and monitoring of the atmosphere. It is shown in Ref. 1 that when a laser beam propagates through the atmosphere the SRS can cause a strong redistribution of the laser pulse energy from the incident radiation to the SRS Stokes component. It should be noted that the Stokes beam has a larger divergence compared to that of the incident beam.

The present paper concerns with theoretical study of a focused laser beam propagation along horizontal atmospheric paths. Within the initial portion of a path the parameters of radiation coincide with those assumed in laser sounding of the atmosphere.[2]

The propagation of sounding radiation along the path is described by the equations for the complex amplitudes of the waves of incident radiation (IR) U_i and the Stokes component (SC) U_S. The equations describe the diffraction of waves in space, their interaction in the process of SRS, and losses in the medium

$$\frac{\partial U_i}{\partial z} + \frac{i}{2\kappa_i}\Delta_\perp U_i = -\left(g\frac{\omega_i}{\omega_S}|U_S|^2 + \frac{\alpha_i}{2}\right)U_i , \qquad (1)$$

$$\frac{\partial U_S}{\partial z} + \frac{i}{2\kappa_S}\Delta_\perp U_S = \left(g|U_i|^2 - \frac{\alpha_S}{2}\right)U_S , \qquad (2)$$

with the boundary conditions for a focused Gaussian beam

$$U_i(r, 0) = U_{i0} \exp\left[-\left(1 - i\frac{z_d}{z_f}\right)\frac{\overline{r}^2}{2}\right], \qquad (3)$$

where U_{i0} is the amplitude of an incident wave within the central portion of the beam ($r = 0$) in the beginning of the path ($z = 0$), z is the axis oriented along the direction of the beam propagation, r is the radial coordinate, $\overline{r} = r/a$, a is the effective radius of the beam, $\Delta_\perp$ is the transverse Laplacian, $\omega_{i,S}$ and $\kappa_{i,S}$ are the frequencies and wave numbers of the incident radiation and the Stokes component, in the case of SRS $\omega_i - \omega_S = \omega_v$ and ω_v is the frequency of the vibrational (or rotational) transition, $z_d = \kappa_i a^2$ is the length of the diffraction spreading of the beam, z_f is the focusing length, $g = \dfrac{2N\lambda_S^2\lambda_i}{\pi\hbar\Delta\omega_\kappa n_i n_S^2}\cdot\dfrac{d\sigma}{d\Omega}$ is the gain for the Stokes wave for $|U_i| = 1$, N is the number density of molecules along the path, $\Delta\omega_k$ is the linewidth of the vibrational transition, $n_{i,S}$ and $\lambda_{i,S}$ are the refractive index and the wavelength corresponding to the frequencies $\omega_{i,S}$, $\dfrac{d\sigma}{d\Omega}$ is the differential cross section for spontaneous Raman scattering, $\alpha_{i,S}$ are the attenuation coefficient for the incident radiation and the Stokes component, and $\hbar$ is Planck's constant.

The equations are written in a coordinate system moving together with the pulse. The change in the populations of the Raman–active transitions that occur at very high intensities of incident radiation ($I > 10^2$ GW/cm^2) is not taken into account in these equations. It is assumed that the molecules follow the oscillations of the field amplitudes and that the dispersion of their group velocities of the incident and the Stokes radiation pulses is insufficient for the pulses to separate apart on the path. These assumptions are valid for the pulsewidths $t_p > 1/\Delta\omega_\kappa$, $\dfrac{L}{c}|n_i - n_S|$, and L is the length of the path.

As in Ref. 1 we studied stimulated Raman scattering on the vibrational transitions of the nitrogen molecules (VSRS). The stimulated Raman scattering on rotational transitions (RSRS) with lower threshold than that for the VSRS has not been taken into account. Such an approach enabled us to find an important effect of the VSRS on energy characteristics of the high–power pulses propagating along extended paths. The rotational transition frequency is 25–40 times (59 cm^{-1}, 75 cm^{-1}, and 91 cm^{-1}) as low as the vibrational transition frequency (2331 cm^{-1}). As was revealed experimentally[3] a sufficiently high excess of the incident beam power over the VSRS threshold, can result in certain worsening of the beam quality at the far end of the path, though its entire exhaust is not yet observed. This fact can serve as a grounding for a simplified approach in which the effect of the rotational stimulated Raman scattering is neglected.

In the present paper we study the vibrational stimulated Raman scattering of the focused laser beams on the nitrogen molecules along the horizontal atmospheric paths at the altitudes $H = 5$ km and 20 km above the earth's surface. The propagation of a square pulse with the duration $t_i = 10$ ns and the starting energy $E_{i0} \le 2.5$ J has

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been considered. The effective radius of the Gaussian beam a is equal to 10 cm. The values of the medium parameters and the noise seed for the Stokes component $|U_{S0}|$ in the medium and at its boundary are the same as those used in Ref. 1.

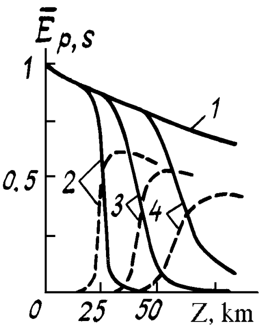

FIG. 1. The pulse energy of the incident radiation E_i (solid lines) and of the Stokes component E_S (dashed curves) as a function of the range z along the direction of propagation for different lengths of the beam focusing: 1) a collimated beam ($z_f = \infty$), 2) $z_f = 30$ km, 3) $z_f = 50$ km, and 4) $z_f = 75$ km. $\bar{E}_{i,S} = E_{i,S}/E_{i0}$, $E_{i0} = E_i$ for $z = 0$.

Equations (1) and (2), by virtue of Eq. (3), were solved using numerical methods. Some computational results for the case of the propagation of a neodymium laser radiation ($\lambda_i = 1.06$ μm) on a path at the altitude of 5 km are shown in Fig. 1 where redistribution of the incident radiation pulse energy over the radiation components

$$E_{i,S} = \frac{c}{2}\int_0^{t_p}\int_0^{\infty} |U_{i,S}(z, r, t)|^2 r\, dr\, dt). \qquad (4)$$

The calculations have been done for the laser beam ($E_{i0} = 2.5$ J) focused at the distances z_f equal to 30 km, 50 km, and 75 km (curves *2*, *3*, *4*). In the case of the collimated beam ($z_f = \infty$, curve *1*) no sufficiently high SC is observed, while in the case of a focused beam there takes place an essential increase of the amplification factor $2g\int_0^z (|U_i(r, z')|^2 - a_S)dz'$ for the SC due to the beam narrowing in the vicinity of the beam caustic. This, in turn, leads to a rapid growth of the SC and, as a result, to a sharp exhaust of the incident radiation pulse. The intensity of the incident radiation within the near zone of the path $I_i = \frac{c}{4\pi}|U_i|^2$ can be written using the formula[4]

$$|U_i|^2 = \frac{|U_{i0}|^2}{\left(1 - \frac{z}{z_f}\right)^2 + \frac{z^2}{z_d^2}} \times$$

$$\times \exp\left[-\frac{r^2}{a^2\left[\left(1 - \frac{z}{z_f}\right)^2 + \frac{z^2}{z_d^2}\right]} - \alpha_f z\right]. \qquad (5)$$

Substitution of Eq. (5) for $r = 0$ into Eq. (2) (in this case $\Delta_\perp U_S = 0$) yields the equation describing the range behavior of the Stokes component along the beam axis the solution of which is

$$|U_S|^2 = |U_{S0}|^2 \exp\left[2g|U_{i0}|^2 z_d\, e^{-\alpha_p z} \times \right.$$

$$\left. \times \arctan\left(\frac{z/z_d}{1 - z/z_f}\right) - \alpha_S z\right]. \qquad (6)$$

As follows from this formula a proper selection of the incident beam parameters at the initial portion of the path can provide for a shift of the region of the effective stimulated Raman scattering where the Stokes component rapidly increases and strongly affects the incident radiation, to the portion of the path located at the distance $z \simeq z_f$. Such localization of the region of the effective stimulated Raman scattering in the region of the beam focusing can be of practical use in the applications of the stimulated Raman scattering. It could be interesting, e.g., to use the Stokes radiation produced in the zone of the effective stimulated Raman scattering, along with the incident radiation for obtaining additional information about the far zone of the lidar sounding path. Using formula (6) one can calculate the radiation parameters within the initial portion of the path which would influence the SRS on the energy characteristics of incident radiation at certain ranges or on the whole path to be negligible.

The possibility of creating such conditions also depends on the medium parameters which determine the values g, α_i, and α_S. As a consequence these conditions vary with height H of the sounding path. Figure 2 shows the behavior of the intensity of incident radiation ($t_p = 10$ ns, $\lambda_i = 1.06$ μm, $E_{i0} = 2.5$ J, a = 10 cm) and of the Stokes component ($\lambda_S = 1.41$ μm) along the paths lying at different altitudes ($H = 20$ km, curves *1* and $H = 5$ km, curves *2*). It is characteristic of higher–altitude paths that the energy losses in the medium are lower because of the decrease in $\alpha_{i,S}(H)$, and the region of the effective stimulated Raman scattering is somewhat displaced to the far end of the path due to the decrease in the ratio $N/\Delta\omega_c$.

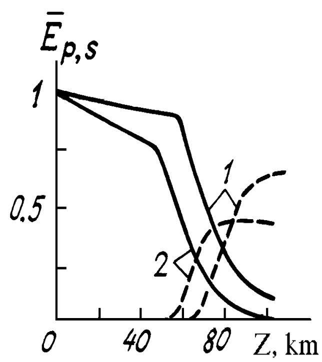

FIG. 2. Behavior of the pulse energy of the incident radiation E_i (solid curves) and the Stokes component E_S (dashed curves) along the direction of propagation z at different altitudes: 1) $H = 20$ km and 2) $H = 5$ km, $\bar{E}_{i,S} = E_{i,S}/E_{i0}$ and $E_{i0} = E_i$ for $z = 0$.

The pulse energy is an integral parameter (see Eq. (4)) and, therefore, its dependence on the distance z in Figs. 1 and 2 does not reflect the change in the distribution of the intensity over the beam cross section along the path. As to the initial interval of the path such an information about the beam of incident radiation can be obtained from formula (5), while the change in the intensity of the Stokes component beam being formed along z is described by expression (6). Shown in Fig. 3 are the distributions of radiation intensity over the cross sections of the incident beam I_i and the Stokes component I_S as functions of a range along the direction of propagation z constructed using the results of numerical solution of the system of equations (1) and (2) taking into account Eq. (3) and for $H = 5$ km, $z_f = 50$ km, other parameters of incident radiation being as follows: $\lambda_i = 0.53$ μm, $E_{i0} = 0.8$ J, $t_p = 10$ ns, and $a = 10$ cm. A 2–fold decrease in the wavelength λ_I results in a 2.9 –fold increase of the value g and, hence, the pulse energy E_{i0} at which the stimulated Raman scattering is effective decreases by a factor of 3. For the third harmonic $\lambda_i = 0.353$ μm of a neodymium laser radiation the stimulated Raman scattering process becomes effective already at $E_{i0} = 0.5$ J.

The narrowing of the beam of incident radiation at the initial portion of the path (the effective radius of the beam $r_{\text{eff}} = a\sqrt{\left(1 - \frac{z}{z_f}\right)^2 + \frac{z^2}{z_d^2}}$ results in an increase of the intensity in the central part of the beam. Therefore, in the region of the effective stimulated Raman scattering the incident pulse is rapidly exhausted, primarily in the central part of the beam, while the formed beam of the Stokes component rapidly increases in the intensity and its radius also increases. After the incident pulse is exhausted the intensity of the Stokes component quickly decreases because of the beam spreading and due to the extinction of radiation in the atmosphere. It should be noted that the Stokes beam is diffracted more rapidly than the incident beam. This is valid both in the case of initially collimated[1] and focused incident beams.

Thus, the focusing of a laser beam on atmospheric paths strongly increases the efficiency of the stimulated Raman scattering. In the region of the beam caustic this results in the complete exhaust of the incident radiation thus blocking its further propagation. If desired, it is possible to localize the effect of the stimulated Raman scattering on a certain interval of the path what can be used in a number of practical applications. For example, this can be used for limiting the length of the path in which the incident radiation should propagate or for creating such a region on the path after which there starts the propagation of radiation at two wavelengths, i.e., at the wavelength of the incident radiation and at that of the Stokes component, or at the wavelength of the Stokes component alone.

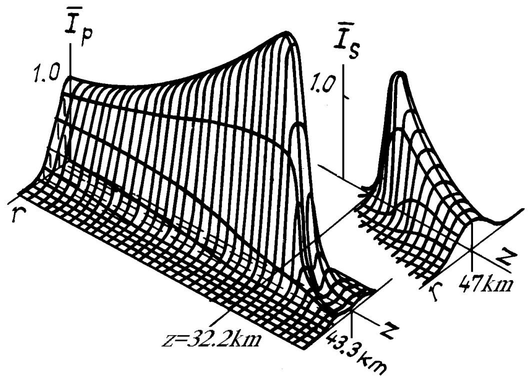

FIG. 3. The distributions of the intensity of incident radiation I_i (solid curves) and of the Stokes component I_S (dashed curves) over the cross section of the beam (r is the radial coordinate) as functions of a range along the direction of propagation z. $\bar{I}_i = I_i/I_{i0}$, $\bar{I}_S = I_S/I_{i0}$ and $I_{i0} = I_i$ for $z = 0$.

Thus, during the propagation of laser radiation through the atmosphere the effect of stimulated Raman scattering on the nitrogen molecules is of fundamental importance not only in the problems of the transfer of high–power laser radiation[1] but also in the problems of laser sounding of the atmosphere. Important also is the competition of the stimulated Raman scattering at rotational and vibrational transitions of molecules. While the stimulated Raman scattering on vibrational transitions of nitrogen molecules becomes noticeable at distances of tens of kilometers, the stimulated Raman scattering on rotational transitions, for which the cross section of Raman scattering is by an order of magnitude larger than that for the vibrational ones can occur at distances of hundreds of meters.[3]

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