STIMULATED RAMAN SCATTERING OF WEAKLY FOCUSED LASER BEAMS PROPAGATING ON VERTICAL ATMOSPHERIC PATHS

M.F. Shalyaev and V.P. Sadovnikov

Institute for Radio Engineering and Electronics of the Russian Academy of Sciences, Moscow

Received August 12, 1993

The effect of stimulated Raman scattering (SRS) on the propagation of weakly focused laser beams on vertical atmospheric paths has been considered. The energy levels of laser pulse being threshold for SRS have been determined for such paths. It has been found that SRS effect intensifies when laser beam propagates in a downward direction in comparison with its propagation in opposite direction.

At present the number of papers devoted to investigations of stimulated Raman scattering (SRS) processes in the atmosphere increases. The ideas and suggestions are put forward that proper allowance must be made for the SRS effect which must be put to practical use on atmospheric paths (see, for example, Refs. 1–3). The above–mentioned papers indicate the urgency of investigations of nonlinear optical effects that manifest themselves in the process of laser radiation propagation on the extended atmospheric paths. These effects can be important for such propagation paths even when the intensity of laser radiation is three orders of magnitude lower than threshold intensities of such effects in cells.

It was shown in Refs. 1 and 2 that propagation of laser beams on horizontal atmospheric paths can be strongly affected by SRS. In Ref. 2 the propagation of the focused pulsed beams, whose parameters correspond to the parameters of radiation used in laser sensing of the atmosphere, was studied. In the given paper we consider the propagation of weakly focused laser beams (focal distance $z_{\rm f} \gtrsim z_{\rm d}$, where $z_{\rm d}$ is the diffraction length) on vertical atmospheric paths. The problems of radiation propagation along slant paths can also be reduced to such cases.

Considerable variations in the parameters of the medium determining the absorption and scattering of radiant energy (among them Raman scattering) are characteristic of the vertical atmospheric paths. The SRS was taken into account solely on N_2 molecules being the principal gaseous component of the atmosphere. The radiation was considered to be linearly polarized, so that the SRS corresponding to vibrational molecule transitions only was taken into account, as in Refs. 1 and 2. High–power circularly polarized laser beams[4] are required to observe SRS on rotational transitions of nitrogen molecules at pressure less than 2 atm. In spite of the fact that the SRS cross section $d\sigma/d\Omega$ on rotational transitions is one order of magnitude larger than that on vibrational transitions at radiation wavelength $\lambda_{\rm inc} = 0.53$ μm for nitrogen, in Ref. 4 SRS on vibrational transitions only was experimentally observed for linear polarization of the radiation field.

The radiation propagation on the path is described by the equations for the complex amplitudes of the waves of the incident radiation (IR) $\mathcal{E}_{\rm inc}$ and the Stokes component (SC) $\mathcal{E}_s$ written down on the basis of assumptions accepted previously in Ref. 1. The equations describe the diffraction of waves in space, their interaction in the process of SRS, and losses in the medium:

$$\frac{\partial \mathcal{E}_{\rm inc}}{\partial z} + \frac{i}{2\,k_{\rm inc}}\,\Delta_\perp \mathcal{E}_{\rm inc} = -\left(g\,\frac{\omega_{\rm inc}}{\omega_s}\,|\mathcal{E}_s|^2 + \frac{\alpha_{\rm inc}}{2}\right)\mathcal{E}_{\rm inc}\,, \qquad (1)$$

$$\frac{\partial \mathcal{E}_s}{\partial z} + \frac{i}{2\,k_s}\,\Delta_\perp \mathcal{E}_s = \left(g\,|\mathcal{E}_{\rm inc}|^2 - \frac{\alpha_s}{2}\right)\mathcal{E}_s\,, \qquad (2)$$

where z is the coordinate in the direction of wave propagation, $\Delta_\perp$ is the transverse Laplacian, $\omega_{{\rm inc},\,s}$ and $k_{{\rm inc},\,s}$ are the frequencies and wave numbers of the IR and SC, $g = \dfrac{N\lambda_{\rm inc}\lambda_s^2}{2\pi h\Delta\omega}\dfrac{d\sigma}{d\Omega}$ is the gain for the Stokes wave with $\mathcal{E}_{\rm inc} = 1$, $d\sigma/d\Omega$ is the differential cross section for spontaneous Raman scattering, $\lambda_{{\rm inc},\,s}$ are the wavelengths and $\alpha_{{\rm inc},\,s}$ are the attenuation coefficients for the IR and SC, h is Planck's constant, N is the number density of Raman–active molecules along the path, $\Delta\omega = \pi\Delta f$, and Δf is the line width of the Raman transition.

For vertical path we must take into account the variations of the parameters entering into Eqs. (1) and (2) and determining the absorption of radiation components, $\alpha_{{\rm inc},\,s}$, and the efficiency of the SRS, namely, of Δf and number density of nitrogen molecules N. The optical density of the medium becomes smaller when laser beam propagates in the upward direction. This determines the different conditions of the appearance and amplification of the Stokes component during IR propagation in opposite directions: upward and downward.

In practice the beam is often focused at the start of the path to decrease its diffraction divergence. As shown in Ref. 2, strong focusing ($z_{\rm f} < z_{\rm d}$) intensifies the SRS process displacing its effective zone in the beam focal region. Here the case of weak focusing of the beam ($z_{\rm f} \gtrsim z_{\rm d}$) is considered which allows one to decrease beam divergence on distances shorter than $z_{\rm d}$.

It was assumed in calculations that a square pulse with duration of 10 ns consisting of the biharmonic of a neodimium laser at $\lambda_{\rm inc} = 0.53$ μm is emitted at the start of the path. The amplitude distribution over the beam cross section at $z = 0$ is described by the Gaussian curve

$$\mathcal{E}_{\rm inc}(r,\,0) = \mathcal{E}_{\rm inc\,0}\,\exp\left[-\left(1 - i\,\frac{z_{\rm d}}{z_{\rm f}}\right)\frac{\overline{r}^2}{2}\right], \qquad (3)$$

0235-6880/94/01 20-03 $02.00

where $\mathcal{E}_{\rm inc\,0}$ is the amplitude at the beam center ($r = 0$), r is the radial coordinate, $\overline{r} = r/a$, and a is the effective beam radius. We obtain $z_{\rm d} \simeq 30$ km with these parameters. In calculations $z_{\rm d}$ was set to be equal to 40 km. Vertical profiles of the atmospheric parameters N, Δf, and $\alpha_{\rm inc,\,s}$ were borrowed from Refs. 5 and 6.

Equations (1) and (2) were numerically solved with boundary condition (3). The seed for the SC in the medium at the start of the path was determined in analogy with Refs. 1 and 2. The variation of the energy $E_{\rm inc,\,s}$ of radiation components was calculated from the solutions of Eqs. (1) and (2) using the following formula:

$$E_{\rm inc,\,s}(z) = \frac{c}{2} \int_0^{t_p} \int_0^{\infty} |\mathcal{E}_{\rm inc}(z,\, r,\, t)|^2\, r\, {\rm d}r\, {\rm d}t\ . \qquad (4)$$

Figure 1 shows the plots of $E_{\rm inc,\,s}$ distribution along the path length z. The values $E_{\rm inc,\,s}$ are normalized to the input energy $E_{\rm inc\,0}$ of IR and are calculated for the case of upward propagation on the vertical path (curves *1*, *2*, and *3*) for initial energies $E_{\rm inc\,0}$. It follows from Fig. 1 that small changes in the beam energy at the start of the path have a significant effect on redistribution of the energy between the radiation components. If the SC is not manifested strongly at altitudes above 30 km for $E_{\rm inc\,0} = 0.5$ J, it becomes pronounced already at an altitude of 16 km for $E_{\rm inc\,0} = 0.833$ J for radiation intensity at the beam center $I_{\rm inc\,0} = 640$ kW/cm^2 and increases rapidly during its propagation along the path thereby exhausting the IR. This section of the propagation path was called a zone or a region of effective SRS in Refs. 1 and 2. The variations of the energy of radiation components are no longer observed at altitudes above 30 km, and the SC energy is equal to about 40% of the initial IL energy $E_{\rm inc\,0}$. The further increase in $E_{\rm inc\,0}$ shifts the region of the effective SRS toward the start of the path, and the SC reaches more than 40% at the end of the path while the residual IL energy decreases.

Curve *4* corresponds to the case in which the path starts at an altitude of 2 km. At this altitude α_s decreases two times in comparison with its value at the Earth surface, and $\alpha_{\rm inc}$ decreases by a factor of 1.5. SC gain decreases only by 6% at an altitude of 2 km. Zone of effective SRS starts earlier than in the case in which a beam is transmitted from the Earth surface, and the SC energy contribution increases up to 55% at the end of the path.

The behavior of curves shown in Fig. 1 resembles the behavior of corresponding curves for horizontal paths (see Refs. 1 and 2). Their relative differences are caused by the altitude variation of the parameters of the medium on the vertical paths. The behavior of analogous curves for vertical paths when laser beam propagates in the downward direction differs considerably. Fig. 2*a* shows the dependences of $E_{\rm inc,\,s}/E_{\rm inc\,0}$ on the altitude calculated for $E_{\rm inc\,0} = 0.5$ J when the same beam propagates in the downward direction starting from different altitudes. The SC is not manifested markedly when laser beam propagates in the upward direction, i.e., it is below the recording threshold, where as it increases up to 30% in some cases when laser beam propagates in the downward direction (Fig. 2*a*). The amount of increase depends on the altitude at which the path starts. Consequently, the SRS process is more effective when laser beam propagates in the downward direction. In this case the beam enters thicker medium, what is accompanied by SC gain.

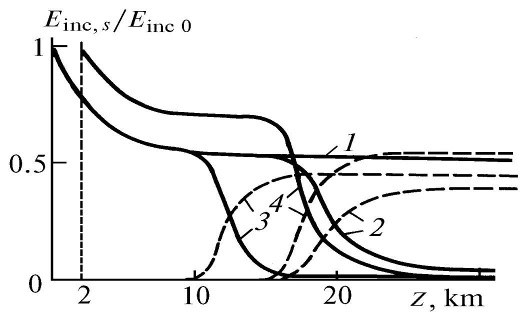

FIG. 1. Distribution of $E_{\rm inc}$ *(solid lines) and* E_s *(dashed lines) along the path.* $E_{\rm inc\,0} = 0.5$ (*1*), 0.833 (*2 and 4*), *and* 1.25 J (*3*) (*path starts at an altitude of* 2 km).

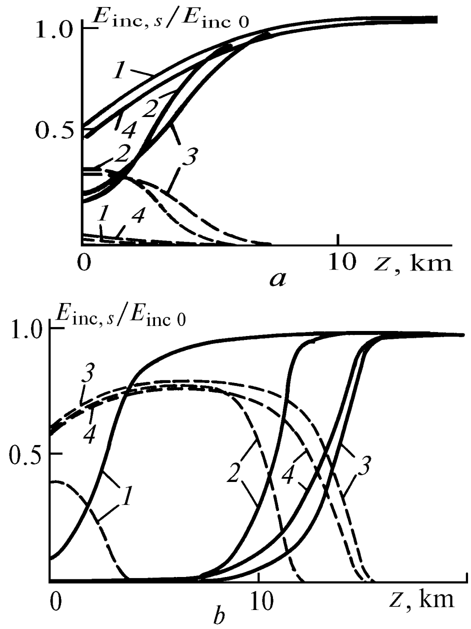

FIG. 2. Distribution of the incident radiation energy $E_{\rm inc}$ (*solid lines*) *and Stokes component energy* E_s (*dashed lines*) *normalized to the initial value* $E_{\rm inc}(z = 0) = E_{\rm inc\,0}$ *along a)* $H = 20$ (*1*), 25 (*2*), 35 (*3*), *and* 40 km (*4*); *b)* $H = 15$ (*1*), 25 (*2*), 35 (*3*), *and* 40 km (*4*).

Fig. 2*b* shows the plots of $E_{\rm inc,\,s}/E_{\rm inc\,0}$ when laser beam propagates along the path in the downward direction with $E_{\rm inc\,0} = 0.833$ J. It is seen from the figure that in separate cases the SC energy can reach 80% of the IL energy at the start of the path.

Thus the energy characteristics differ considerably when the same laser beam propagates in opposite directions. This difference between the characteristics is caused by the distribution of the parameters of the medium in the atmosphere and is increased due to nonlinear dependence of the SRS process on the intensity of radiation. Since SRS manifests itself during propagation of radiation used for laser sensing on the extended atmospheric paths, the algorithms are required which correctly take into account the effect of the SRS on the propagation of radiation through the atmosphere in processing of laser–sensing data.

REFERENCES

1. V.P. Sadovnikov, G.M. Strelkov, and M.F. Shalyaev, Atm. Opt. **2**, No. 11, 953–958 (1989).
2. M.F. Shalyaev and V.P. Sadovnikov, Atm. Opt. **4**, No. 11, 781–783 (1991).
3. Yu.V. Kistenev, Yu.N. Ponomarev, and I.A. Shevchuk, Atmos. Oceanic Opt. **5**, No. 2, 91–92 (1992).
4. V.S. Averbakh, A.I. Makarov, and V.I. Talanov, Kvant. Elektron. **5**, No. 4, 823–829 (1978).
5. V.E. Zuev and V.S. Komarov, *Statistical Models of the Temperature and Gas Components of the Atmosphere* (Gidrometeoizdat, Leningrad, 1986), 246 pp.
6. I.I. Ippolitov, V.S. Komarov, and A.A. Mitsel', *Spectroscopic Techniques for Atmospheric Sensing* (Nauka, Novosibirsk, 1985), 144 pp.