The effect of stimulated Raman scattering on the high-power laser beam propagation through the atmosphere

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We present the study on determination of the intensity of laser radiation having different wavelengths and widths of generation spectrum when strong influence of stimulated Raman scattering (SRS) must be observed on the propagation of radiation in the atmosphere.

Introduction

At propagation of high-power laser radiation through the atmosphere, the effects of stimulated light scattering can arise because of a build-up of seed thermal oscillations under the action of incident and scattered waves.[1] This build-up of intramolecular oscillations results in the stimulated Raman scattering (SRS). The first theoretical estimates of the SRS increment were made by Pasmannik and Talanov.[2] During the past few years many experimental studies have been carried out on determining the cross sections of spontaneous Raman scattering for different molecules of the air[3] and its frequency dependence.[4] This made it possible to assess fully the effect of SRS on the propagation of a high-power laser beam along different optical paths in the atmosphere.

1. Theory of stimulated Raman scattering in the forward direction

The number of quanta spontaneously scattered by a scattering medium of the length dZ within a solid angle dΩ, for one polarization, is expressed in terms of the scattering cross section $\sigma_{\rm sp}$ as follows[5]:

$$(\mathrm{d}N_{\rm s})_{\rm sp} = N_{\rm a}\, N_{\rm l}\, \frac{\partial\sigma_{\rm sp}}{\partial\Omega}\, \mathrm{d}\Omega\, \mathrm{d}z, \qquad (1)$$

where $N_{\rm a}$ is the number of molecules per unit volume in the lower energy state, and $N_{\rm l}$ is the number of incident laser radiation quanta, $N_{\rm s}$ is the number of scattered quanta at the frequency $\omega_{\rm s}$,

$$N_{\rm l,s} = \varepsilon E^2/2\pi\hbar\omega_{\rm l,s}.$$

Consequently, the intensity of spontaneously scattered light per unit length within a solid angle dΩ can be determined as follows:

$$J_{\rm sp}(z) = N_{\rm a}\, \frac{\partial\sigma_{\rm sp}}{\partial\Omega}\, \mathrm{d}\Omega\, J_{\rm l}(0) \left(\frac{\omega_{\rm s}}{\omega_{\rm l}}\right)\left(\frac{n_{\rm l}}{n_{\rm s}}\right), \qquad (2)$$

where $J_{\rm l}(0)$ is the intensity of incident radiation, $\omega_{\rm l}$, $\omega_{\rm s}$ are frequencies of the exciting and Stokes radiation.

In Eq. (2) z relates to the place of spontaneous scattering origination. In the linear region (no saturation occurs), the equation for the intensity of the Stokes SRS in the forward direction takes the form

$$\frac{\partial J_{\rm s}}{\partial z} = G_{\rm Ram}\, J_{\rm s}(z)\, J_{\rm l}(0) + N_{\rm a} \frac{\partial\sigma_{\rm sp}}{\partial\Omega}\, \mathrm{d}\Omega\, J_{\rm l}(0) \left(\frac{\omega_{\rm s}}{\omega_{\rm l}}\right)\left(\frac{n_{\rm l}}{n_{\rm s}}\right). \qquad (3)$$

Here we neglected the optical losses. If no external source of the Stokes radiation exists, the boundary condition $J_{\rm s}(z = 0) = 0$ should hold. From Eq. (3) we can derive

$$J_{\rm s}(L) = N_{\rm a} \frac{\partial\sigma_{\rm sp}}{\partial\Omega}\, \mathrm{d}\Omega \left(\frac{\omega_{\rm s}}{\omega_{\rm l}}\right)\left(\frac{n_{\rm l}}{n_{\rm s}}\right) \frac{1}{G_{\rm Ram}} \{\exp[G_{\rm Ram} J_{\rm l}(0) L] - 1\}. \qquad (4)$$

From Eq. (4), in the absence of radiation amplification $GJ_{\rm l} \to 0$, one obtains the following expression for spontaneous scattering, at $GJ_{\rm l}(0)L \gg 1$:

$$J_{\rm s}(L) = J_{\rm s}^{\rm eq}(0) \exp[G_{\rm Ram} J_{\rm l}(0) L], \qquad (5)$$

where

$$J_{\rm s}^{\rm eq}(0) = N_{\rm a}\, \frac{\partial\sigma_{\rm sp}}{\partial\Omega}\, \mathrm{d}\Omega \left(\frac{\omega_{\rm s}}{\omega_{\rm l}}\right)\left(\frac{n_{\rm l}}{n_{\rm s}}\right) \frac{J_{\rm l}(0)}{G_{\rm Ram}\, J_{\rm l}(0)}. \qquad (6)$$

Therefore, the equivalent input signal $J_{\rm s}^{\rm eq}$ is the intensity of spontaneous Stokes scattering at the interaction length being equal to the inverse value of the linear gain $1/g_{\rm Ram} = 1/G_{\rm Ram}\, J_{\rm l}(0)$.

According to Ref. 6 the SRS gain is as follows:

$$g_{\rm Ram} = G_{\rm Ram} J_{\rm l}(0) = N_{\rm a} \frac{\partial\sigma_{\rm sp}}{\partial\Omega} \left(\frac{8\pi n_{\rm s} n_{\rm l}}{\omega_{\rm l} c}\right)\left(\frac{c^3}{\nu_{\rm s}^2 n_{\rm s}^3}\, h(\nu_{\rm s})\right) J_{\rm l}(0), \qquad (7)$$

where $\nu_{\rm s}^2\, n_{\rm s}^3/c^3$ is the number of vacuum oscillators related to the unit solid angle, unit volume, and a unit frequency range; $h(\nu_{\rm s})$ being the density of states of the Raman transition

$$h(\nu_{\rm s}) = \frac{\hbar\Gamma_{\rm ab}/\pi}{\hbar^2(\omega_{\rm l} - \omega_{\rm s} - \omega_{\rm ab})^2 + \hbar^2\Gamma_{\rm ab}^2} \qquad (8)$$

represents a dispersion curve determined by the attenuation constant $\Gamma_{\rm ab}$ corresponding to the pair of

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the energy levels of the system involved in the transition. In the case of resonance, $\omega_l - \omega_s = \omega_{ab}$, this function is inversely proportional to the width and equals $1/\Gamma_{ab}\hbar\pi$.

Thus, at a resonance $\omega_l - \omega_s - \omega_{ab} = 0$,

$$g_{Ram} = N_a \frac{\partial\sigma_{sp}}{\partial\Omega}\left(\frac{c^3}{\nu_s^2 n_s^3}\right)\left(\frac{8\pi n_s n_l}{\omega_l c\hbar\Gamma}\right)J_l(0) = \frac{8}{\pi}N_a\frac{\partial\sigma_{sp}}{\partial\Omega}\frac{\lambda_s^2\lambda_l}{\Delta c^2 h}J_l(0), \quad (9)$$

where $\Delta = \Gamma/\pi c$, cm^{-1}; $n_s \approx n_l = 1$.

With regard for the optical losses $g_{Ram} = -2K_\omega + G_{Ram}J_l(0)$, that means that there is a threshold intensity value of $J_l(0)$. When operating to zenith from an altitude $H_0 \approx 10$ km, the temperature varies slightly with the altitude, and hence the variation of molecular concentration with altitude $N_a(H)$ can be represented[7] as

$$N_a(H) = \frac{P_0}{m_m RT_0}\exp\left[-\frac{g_c}{RT_0}(H - H_0)\right], \quad (10)$$

where R is the specific gas constant $R \approx 287.05$ J/kg·K; g_c is the standard acceleration of gravity; m_m is the mass of molecule; T_0 is the absolute temperature. In this case

$$\int_{H_0}^{H} g_{Ram}\mathrm{d}H = $$

$$= \frac{8}{\pi}N_{a0}\frac{\partial\sigma_{sp}}{\partial\Omega}\frac{\lambda_s^2\lambda_l}{\Delta c^2 h}\frac{RT}{g_c}\left[1 - \exp\left(-\frac{g_c}{RT}(H - H_0)\right)\right], \quad (11)$$

where $N_{a0} = \frac{P_0}{m_m RT_0}\eta = \frac{\rho_0}{m_m}\eta$, η is the content of a gas component in the atmosphere.

It is seen from Eq. (11) that the total amplification of the Stokes SRS is stabilized at $\frac{g_c}{RT}(H - H_0) \gg 1$ and depends on H_0 since $N_{a0} = f(H_0)$; and vice versa, at $\frac{g_c}{RT}(H - H_0) \ll 1$ Eq. (5) is valid at $L = (H - H_0)$.

For a slant path

$$g_{Ram}\int_0^L \mathrm{d}z = G_{Ram}J_l(0)\frac{RT}{g_c\cos\theta}\left[1 - \exp\left(-\frac{g}{RT}L\cos\theta\right)\right],$$

where θ is the angle between the direction of the path and zenith. For $L \gg \frac{RT}{g_c\cos\theta}$ by analogy with (11) we obtain

$$g_{Ram}\int_0^L \mathrm{d}z = G_{Ram}J_l(0)\frac{RT}{g_c\cos\theta}. \quad (12)$$

At $\theta \approx 90°$ one obtains Eq. (6).

For a convective instability (see Eq. (5)), when SRS occurs at a constant medium density, after exceeding the threshold for the strongest combination mode no threshold conditions for the SRS on other modes can be realized because of the pump depletion with the increasing L. Therein lies the main limitation of the application of the SRS as a spectroscopic technique.

If the molecular concentration along the path of radiation propagation varies according to Eq. (10), this limitation is removed.

2. Comparison of the SRS in the forward and backward directions of scattering

At a pulsed excitation of the SRS, if the duration of the pump pulse is shorter than the time of light propagation through the medium, the SRS gain in the backward direction is found to be severely limited due to the following factors:

– the limited range of interaction of the pump and Stokes pulses;

– the finite width of the pump line, $2\Gamma_l$, as a rule, is larger than $2\Gamma_{ab}$.

As the theory predicts,[6] the peak of the SRS gain in the backward direction is proportional to $(2\Gamma_{ab} + 2\Gamma_l)^{-1}$, whereas for the forward direction the gain is proportional to Γ_{ab}^{-1} under condition that[8]

$$\frac{2\Gamma_l}{2\pi c} = \Delta\nu_l \ll \frac{1}{2\pi}G_{Ram}J_l(0)\frac{u}{\delta u}, \quad (13)$$

where $\delta u/u$ is the relative dispersion of the group velocities of the Stokes component and the exciting radiation[9]:

$$\frac{\delta u}{u} = \left[\frac{1}{u_s} - \frac{1}{u_l}\right]c,$$

$$\frac{1}{u} = \frac{\partial K}{\partial\omega} = \frac{\partial(n\omega/c)}{\partial\omega} = \frac{n}{c} + \frac{\omega}{c}\frac{\partial n}{\partial\omega}.$$

Having used the formula for the refractive index of the air in the atmosphere[10]

$$n - 1 = 10^{-6}\cdot 222.7(1 + 7.53\cdot 10^{-3}\lambda^{-2})\,\rho,$$

where the dimensionality of ρ is in kg/m^3 and λ is in μm, can be derived in the form

$$\frac{\delta u}{u} = 3\cdot 222.7\cdot 7.53\cdot 10^{-9}\rho\left[\frac{\lambda_l^2 - \lambda_s^2}{\lambda_l^2\lambda_s^2}\right] \approx 10^{-6}\text{–}10^{-7}. \quad (14)$$

At forward scattering in the medium with small dispersion a short segment of train of the Stokes wave always interacts coherently with one and the same part of the pumping wave train. At backscattering, on the contrary, segments of trains of interacting waves continuously move relative to each other. The Stokes wave all time meets a new pumping wave front. Therefore, the SRS gain in the forward direction quasistatically follows the change of the pumping wave intensity and is proportional to Γ_{ab}^{-1} as is predicted by the above-mentioned stationary theory.

Under conditions of the Earth's atmosphere the shape of molecular spectral lines is determined by the action of the following three effects[11]:

– the natural line width determined by the molecular structure;

– the Doppler effect;

– the collision of molecules.

In the atmosphere the Doppler effect becomes noticeable at altitudes of the stratosphere (the altitudes more than 10–15 km) and dominates at higher altitudes.[10] In the troposphere the basic effect of broadening, i.e., the collision of molecules, is described by the Lorentz contour.

The joint action of Doppler effects and collisions of molecules, which act simultaneously in the atmosphere, but with different contribution at different altitudes, results in the Voigt line contour.

The value for the Lorentz widths in the ground layer ($\rho = \rho_c$) is, on the average, $\Delta\nu_L \approx 0.1$ cm^{-1} (see Ref. 11). Consequently, if

$$2\Gamma_{ab} \approx \Delta\nu_D + B\frac{\rho}{\rho_c},$$

the altitude, at which $\Delta\nu_D = \Delta\nu_L$ is about 25 km, where $\Delta\nu_D$ is the Doppler width

$$\Delta\nu_D/\nu_{ab} = 2\sqrt{\frac{2kT\ln 2}{m_m c^2}}, \quad (15)$$

$$\Delta\nu_D \approx (3\text{–}4.4)\cdot 10^{-3}\ \text{cm}^{-1}.$$

Therefore to assess the above factors it is assumed that up to 25 km the increment of SRS is independent of pressure because $N_a/2\Gamma_{ab}$ = const. At high altitudes ($H > 25$ km), $2\Gamma_{ab} \approx$ const and in this case it is necessary to use the expression (11).

The most intense molecular Raman transitions[12] correspond to $\Delta J = \pm 2$, $\Delta v = 0$, (i.e., purely rotational transitions) or $\Delta J = 0$, $\Delta v = \pm 1$ (i.e., purely vibrational transitions). Here J is the quantum number of the net momentum, and v is the vibrational quantum number. Transitions of the first type are denoted by $S_0(J)$, and those of the second type are denoted by $Q(J)$ where J relates to the initial rotational level. Normally the lines of Q-branches have higher intensity.

3. Results and discussion

The calculated results on the SRS in the atmosphere are given in Table 1. The radiation sources are positioned onboard an aircraft moving at 10 km altitude ($H_0 = 10$ km), the operation is performed in zenith, $\delta\Omega = (3\cdot 10^{-5})^2$ sr.

Stokes shifts for the $Q(J)$ transitions of the main components of air (N_2 and O_2) as well as the values of cross sections of spontaneous Raman scattering at $\lambda = 0.3371$ μm were taken from Ref. 3. With due regard for the frequency dependence[4] these values were calculated for different wavelengths of the exciting radiation (see Table 1):

$$\sigma_{sp} \approx \left(\frac{\omega_l - \omega_{ab}}{\omega_l}\right)^4. \quad (16)$$

As is seen from Table 2, the maximum values of G_{Ram} at $\Delta\nu_L \approx \Delta\nu_D$ are obtained for HF and CO lasers; the intensity of exciting radiation, at which 10% of energy is pumped to the Stokes component, are $1.3 \cdot 10^3$ and $2 \cdot 10^3$ W/cm^2. For $\lambda = 1.315$ μm, oxygen-iodine laser (OIL), $J_l^{max} \approx 4.8 \cdot 10^3$ W/cm^2.

Table 1

Exciting radiation, λ_l, μm, ν_l, cm^{-1}	Molecule	$\nu_{ab} = \omega_{ab}/2\pi c$, cm^{-1}	λ_{as}, λ_s, μm	ν_{as}, ν_s, cm^{-1}	$\partial\sigma/\partial\Omega$, cm^2/sr	J_s^{eq}, W/cm^2	G_{Ram}, cm/MW
0.3371 29665	N_2	2231	0.3135 0.3645	31896 27434	$3.5\cdot 10^{-30}$		
	O_2	1556	0.3203 0.3557	31221 28109	$4.2\cdot 10^{-30}$		
0.308 32467	N_2	2231	0.288 0.331	34698 30236	$3.51\cdot 10^{-30}$	$2.85\cdot 10^{-11}$	$0.76\cdot 10^{-4}$
	O_2	1556	0.3235	30911	$4.3\cdot 10^{-30}$	$2.13\cdot 10^{-11}$	$0.38\cdot 10^{-4}$
3.0 3333.3	N_2	2231	1.797 9.072	5564.3 1102.3	$5.7\cdot 10^{-32}$	$1.38\cdot 10^{-15}$	$0.92\cdot 10^{-2}$
	O_2	1556	2.04 5.63	4889 1777	$5\cdot 10^{-31}$	$3.9\cdot 10^{-15}$	$0.135\cdot 10^{-1}$
5.0 2000	O_2	1556	2.81 22.5	3356 444	$1.26\cdot 10^{-32}$	$6.2\cdot 10^{-15}$	$0.91\cdot 10^{-2}$
1.315 7604.6	N_2	2231	1.017 1.861	9835.6 5373.6	$1.2\cdot 10^{-30}$	$1.57\cdot 10^{-13}$	$0.35\cdot 10^{-2}$
	O_2	1556	1.091 1.653	9161 6049	$1.97\cdot 10^{-30}$	$1.5\cdot 10^{-14}$	$0.2\cdot 10^{-2}$

Table 2

Excited radiation, λ_l, μm	Molecule	G_{Ram}, cm/MW	Effective path length, cm	$J_l^{max}(0)$ at $J_s = 0.1J_l$, W/cm^2	$\delta u/u$	J^* coherent SRS, W/cm^2	P at $S = 10^4$	θ_{cone}, rad
	I. To zenith from 10 km altitude							
0.308	N_2	$0.76 \cdot 10^{-4}$	$21.35 \cdot 10^5$	$2.1 \cdot 10^5$	$3 \cdot 10^{-5}$	–	–	–
3.0	O_2	$0.135 \cdot 10^{-1}$	$21.35 \cdot 10^5$	$1.3 \cdot 10^3$	$2 \cdot 10^{-7}$	–	–	$0.45 \cdot 10^{-4}$
5.0	O_2	$0.91 \cdot 10^{-2}$	$21.35 \cdot 10^5$	$2 \cdot 10^3$	$2 \cdot 10^{-8}$	$2.8 \cdot 10^3$	–	$0.64 \cdot 10^{-4}$
1.315	N_2	$0.35 \cdot 10^{-2}$	$21.35 \cdot 10^5$	$4.8 \cdot 10^3$	$4 \cdot 10^{-7}$	1	–	$2 \cdot 10^{-4}$
	II. Horizontal (H up to 25 km) and to the lower hemisphere							
5.0	O_2	$0.91 \cdot 10^{-2}$	$400 \cdot 10^5$	$0.9 \cdot 10^2$	$2 \cdot 10^{-8}$	$2.8 \cdot 10^3$	$10 \cdot 10^6$	–
1.315	N_2	$0.35 \cdot 10^{-2}$	$400 \cdot 10^5$	$2 \cdot 10^2$	$4 \cdot 10^{-7}$	1	$2 \cdot 10^6$	–

These intensities should be considered as maximum because they are obtained for the operation along the zenith. For slant paths the intensities decrease according to Eq. (12) as $J_l^{max} \cos\theta$. For horizontal paths, and when operating to the lower hemisphere at the visibility $L \approx 400$ km

$$J_l^{max} \text{ (OIL)} \approx 2 \cdot 10^2 \text{ W/cm}^2,$$

$$J_l^{max} \text{ (CO)} \approx 0.9 \cdot 10^2 \text{ W/cm}^2.$$

Because $G_{Ram}\, J_l(0) \approx 10^{-5}$–$10^{-6}$ cm^{-1} far exceeds the optical losses $2K_\omega \approx 10^{-8}$ cm^{-1}, then SRS is realized at a considerable excess above the threshold value.

Under such operating conditions, when no pump saturation is yet reached, one can expect that along with the Stokes component the anti-Stokes component can appear with the same gain due to the four-wave interaction[6,13]

$$2\mathbf{K}_l = \mathbf{K}_s + \mathbf{K}_{as},$$

where $\mathbf{K}_i$ denotes the wave vectors of laser, the Stokes and anti-Stokes radiation.

If the Stokes radiation propagates in the direction of exciting light, then from the vector diagram it follows that the anti-Stokes radiation is scattered along the cone, whose axis coincides with the direction of incident light, and the angle is formed between this direction and the direction of the cone generating line[13]

$$\theta_{cone}^2 \approx \frac{\omega_l - \omega_{ab}}{\omega_l + \omega_{ab}} (\Delta n_{as} - \Delta n_s); \qquad (17)$$

$$\Delta n_{as} = n_{as} - n_l,\ \Delta n_s = n_l - n_s.$$

Using the formula for the refractive index of air, the following equation can be derived

$$(\Delta n_{as} - \Delta n_s) = \frac{1677\rho_0 \cdot 10^{-9}}{\lambda_{as}^2 \lambda_s^2 \lambda_l^2} =$$

$$= [\lambda_s^2(\lambda_l^2 - \lambda_{as}^2) - \lambda_{as}^2(\lambda_s^2 - \lambda_l^2)].$$

The angle $\theta_{cone} \approx 10^{-3} - 10^{-4}$ rad.

With the increase of the radiation intensity, as compared with the maximum ones, the SRS of higher orders must be excited.[6]

The Stokes and anti-Stokes components of the first order SRS are accompanied by the radiation of Stokes and anti-Stokes components of higher orders. In contrast to overtones in the spontaneous scattering, their frequencies equal to $\omega_l + n\omega_{ab}$, where n is the integer. This peculiarity points to the fact that they are generated more or less sequentially. The anti-Stokes scattering in this case forms a series of light cones. The nearest cone corresponds to the frequency $\omega_l + \omega_{ab}$, the subsequent ones correspond to the frequencies $\omega_l + 2\omega_{ab}$, $\omega_l + 3\omega_{ab}$, and so on.

At the pulsed excitation of SRS the estimates are valid under conditions of stationarity[6]

$$\tau_p > g_{Ram} L/\Gamma. \qquad (18)$$

Besides, by Eq. (6), the wave train length ($c\tau_p$) must be larger than the length of interaction range, being equal to the inverse value of the gain factor, i.e.,

$$\tau_p > 1/(g_{Ram}\, c). \qquad (19)$$

Taking into account these conditions, one can show that $\tau_p > 10^{-6}$ s.

Eq. (13) at $J_l(0) \approx J_l(z)$ can be written as:

$$J_l^* = \frac{2\pi\Delta\nu_l \delta u}{G_{Ram}\, u}. \qquad (20)$$

At $J_l > J_l^*$, when the dispersion of the group velocities is insignificant, the regime of SRS is coherent.[9] The key feature of the coherent regime lies in the fact that, in spite of a wide range of pumping, the increment of gain is determined by its integral intensity ($g_{Ram} = G\bar{J}_l = G\Sigma J_n$), i.e., the entire pumping range participates in the amplification of each spectral line of the Stokes wave. At $J_l < J_l^*$ the break-down of coherent regime occurs; only one pumping mode participates in the amplification of each Stokes mode, which is in resonance with it.

The use of the model of multimode pumping[9] when the distance between the modes $\Delta\nu_M > \Delta\nu_{ab}$ enables us to give a complete pattern of the SRS in the field of a specified noise pumping and to follow the relationship between the increment and the spectrum width and shape.

Thus, for a rectangular shaped spectrum of a multimode pump $I_n = J_0$ ($n = 0 \pm 1 \ldots \pm N$), $\bar{J}_0 = (1 + 2N)J_0$, at $N = 4$, i.e., 9 bands of the vibrational spectrum are involved.

For a CO laser we have

$$J^* = \frac{2\pi\Delta\nu_l}{G_{Ram}} \frac{\delta u}{u},$$

$\Delta\nu_l = 2N \cdot \Delta\nu_M$, $\Delta\nu_M = 25$ cm^{-1}; $\Delta\nu_l = 200$ cm^{-1}; $G_{Ram} = 0.91 \cdot 10^{-8}$ cm/W; $\delta u/u = 2 \cdot 10^{-8}$; $J^*_{CO} = 2.8 \cdot 10^3$ W/cm^2; $J_l|_0 = 2 \cdot 10^3$ W/cm^2 at $\theta_s = 0$. $J_l|_{90^\circ} = 10^2$ W/cm^2 at $\theta_s = 90°$, i.e. $J^*_{CO} > J_l|_0$; $J_l|_{90^\circ}$.

For OIL $\Delta\nu_l \approx 10^{-3}$ cm^{-1}; $G_{Ram} = 0.35 \cdot 10^{-8}$ cm/W; $\delta u/u = 4 \cdot 10^{-7}$; $J^*_{OIL} = 1$ W/cm^2; $J_l|_0 = 4.8 \cdot 10^3$ W/cm^2; $J_l|_{90^\circ} = 2 \cdot 10^2$ W/cm^2, i.e. $J_l|_0$; $J_l|_{90^\circ} > J^*_{OIL}$

Consequently, the operating conditions for the forward SRS of OIL radiation ($\lambda = 1.315$ μm) provide a coherent mode, while for CO laser ($\lambda = 5$ μm) the coherent regime is realized for each vibrational-rotational generation band independently. Therefore, for an identical system of radiation generation the power emitted along the path without a significant effect of SRS for CO laser is by about 5 times greater than for OIL. The coherent regime of the SRS in the backward direction will take place at the intensities[8]

$$J_l > J^* = 2\pi\Delta\nu_l / G_{Ram},\ J^*(\text{OIL}) = 1.8 \cdot 10^6 \text{ W/cm}^2;$$
$$J^*(\text{CO laser}) = 1.4 \cdot 10^{11} \text{ W/cm}^2.$$

4. Conclusion

Thus, based on the above analysis we have determined the laser radiation intensities of different wavelengths and generation spectral widths, at which a considerable effect of SRS is observed on different paths of radiation propagation in the atmosphere. Further refinement of these values is possible on the basis of the experimental investigations of the line widths of combination transitions in N_2 and O_2 under atmospheric conditions.

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References

1. V.E. Zuev, *Laser Radiation Propagation in the Atmosphere* (Moscow, Radio i Svyaz, 1981).
2. G.A. Pasmannik and V.I. Talanov, *in: Abstracts of Reports at the XIth All-Union Conference on Radio Wave Propagation*, (Moscow, Nauka, 1975), pp. 57–60.
3. V.P. Kozubovski, Z.I. Perchi, and G.D. Romanenko, Kvant. Elektron. (Kiev, Naukova Dumka, 1980), Issue 18, pp. 86–107.
4. I.I. Kondilenko, P.A. Korotkov, and O.K. Kostko, Kvant. Elektron. (Kiev, Naukova Dumka, 1977), Issue 12, p. 24.
5. N. Blombergen, Usp. Fiz. Nauk **97**, No. 2, 307–352 (1969).
6. I.P. Shen, *Principles of Nonlinear Optics* (Nauka, Moscow, 1989).
7. V.E. Zuev, ed., *Optical Models of the Atmosphere* (Tomsk Affiliate of SB RAS, Tomsk, 1987).
8. Yu.E. D'yakov, Pis'ma Zh. Exp. Teor. Fiz. **11**, 362–364 (1970).
9. S.A. Akhmanov, Yu.E. D'yakov, A.S. Chirkin, *Introduction to Statistical Radiophysics and Optics* (Nauka, Moscow, 1981), 640 pp.
10. V.P. Aksenov, V.A. Banakh, V.V. Valuev, V.E. Zuev, V.V. Morozov, I.N. Smalikho, and R.Sh. Tsvyk, *High-Power Laser Beams in the Randomly Inhomogeneous Atmosphere*, ed. by V.A. Banakh (Publ. House SB RAS, Novosibirsk, 1998), 341 pp.
11. A.A. Mitsel and Yu.N. Ponomarev, *Optical Models of the Molecular Atmosphere* (Nauka, Novosibirsk, 1988), 128 pp.
12. M.A. El'yashevich, *Atomic and Molecular Spectroscopy* (Fizmatgiz, Moscow, 1962), 892 pp.
13. A. Pekara, *New Appearance of Optics* (Sov. Radio, Moscow, 1973), 263 pp.