EXPLOSIVE ABSORPTION EFFECT OF POWER CO₂ LASER BEAM IN ATMOSPHERE**V.I. ZAKHAROV, V.M. SHMELEV and A.I. NESTERENKO***Laser-Test Division, The SORUS Co. Ltd., Zarechny settl., "Takhov" 104,
Sverdlovsk reg. 624051, USSR*

Abstract—The interaction of a wide beam of intense 10.6 μm and 9.4 μm laser radiation with atmospheric CO₂ is studied. The threshold spectroscopic effect of explosive absorption have been obtained. In this effect the absorption coefficient of the atmosphere increases sharply owing to strong self-heating ($\Delta T \sim 700\text{--}1000\text{ K}$) of the beam channel.

I.—Introduction.

The problem of the transfer of power laser radiation in the atmosphere over large distances with low losses is actual [1]. For this purpose CO₂-laser beams with diffraction divergence and whose diameter is large are employed. In this case of weak removal of heat from the propagation channel occurs and explosive absorption of CO₂ laser radiation owing to thermal explode leading to sharp "darkening" of the atmosphere can arise. The mechanism of explosive absorption of resonance radiation in gases is possible when the absorbing level is not the ground state. In this case the positive feedback occur between the absorption at the resonance transition and the increase of the number of molecules in the absorbing level. Explosive absorption on vibration transitions in molecules was studied theoretically in Refs.2,3 and experimentally in Ref.4.

2.—Thermal instability of power CO₂-laser beam channel in atmosphere.

The purpose of this work is to determine the possible thermal states

of the CO_2 laser beam channel in the atmosphere, the conditions under which thermal instability in the atmosphere arises and explosive absorption process develops.

The attenuation of radiation propagating in the atmosphere is determined by Bougier's law $I_{\alpha,\nu} = I_0 \exp\{-K_{\nu}(t)z\}$.

The absorption coefficient $K_{\nu}(t)$, because it is small for $10.6\mu\text{m}$ and $9.4\mu\text{m}$ radiation, depends on the time t and does not depend on the coordinate z ; $I_{\alpha,\nu}$ is the intensity of the radiation at a point with the coordinate z at the time t ; and I_0 is the starting intensity of laser beam. The value of $K_{\nu}(t)$ in the range of $10.6\mu\text{m}$ and $9.4\mu\text{m}$ is determined by the difference of the populations of the states (100) and (001) ; (020) and (001) of CO_2 :

$$\begin{aligned} K_{\nu}^{10.6\mu\text{m}}(t) &= \sigma_1 (N_{(100)}(t) - N_{(001)}(t)), \\ K_{\nu}^{9.4\mu\text{m}}(t) &= \sigma_2 (N_{(020)}(t) - N_{(001)}(t)), \end{aligned} \quad (1)$$

where σ_1 the cross-section for absorption on the transition $(100)-(001)$ and σ_2 is on the transition $(020)-(001)$.

A simplified kinetic scheme of the relaxation process accompanying the passage of intense $10.6\mu\text{m}$ and $9.4\mu\text{m}$ radiation in atmospheric air is given in Fig.1.

Fig.1. Kinetic scheme of processes which lead to a thermal explosion in the channels of $\lambda=10.6\mu\text{m}$ and $\lambda=9.4\mu\text{m}$ laser beams.

Reactions presented on Fig.1 indicates the existence of positive feedback between intense absorption on the transitions (100) - (001), (020) - (001) and an increase in the population of (100) and (020) levels as a result of heating the atmosphere in the channel of power CO₂ laser beam accompanying V-T relaxation of nitrogen and CO₂.

A qualitative analysis of explosive absorption in the scheme of levels studied above can be performed with the help of one-mode model (see Ref.3.) with the generalized relaxation time

$$\tau_{\Sigma_j} = \left(\frac{x}{\tau_{\text{CO}_2-\text{N}_2}} + \frac{x}{\tau_{\text{CO}_2-\text{H}_2\text{O}}} + \frac{1}{\tau_{\text{N}_2-\text{H}_2\text{O}}} + \frac{1}{\tau_{\text{N}_2-\text{O}_2}} + \frac{1}{\tau_{\text{N}_2-\text{N}_2}} \right)^{-1} \quad (2)$$

where $\tau_{\text{CO}_2-\text{N}_2}$, $\tau_{\text{CO}_2-\text{H}_2\text{O}}$, $\tau_{\text{N}_2-\text{H}_2\text{O}}$, $\tau_{\text{N}_2-\text{O}_2}$ and $\tau_{\text{N}_2-\text{N}_2}$,

are the characteristic times of the relaxation processes above, Fig.1, x is the ratio of the concentrations of CO₂ and N₂; and, for the atmosphere $x=4 \cdot 10^{-4}$. Assuming that the lower levels (100) and (020) in CO₂ is thermalized, in the one-mode model we obtain the following system of two equations (equation of vibrational kinetics and the heat-balance equation):

$$\frac{dn}{dt} = \frac{1}{\tau_{\Sigma_j}} (\bar{n} - n) + \frac{1}{\tau_{pj}} (\bar{n}_j - n) ; \quad (3)$$

$$\frac{dT}{dt} = A \frac{1}{\tau_{\Sigma_j}} (n - \bar{n}) + \frac{1}{\tau_0} (T - T_0) ;$$

where $j=1$ for 10.6 μm radiation and $j=2$ for 9.4 μm , τ_{Σ_1} correspond the

transition $\text{CO}_2^{(001)} - \text{CO}_2^{(100)}$, and τ_{Σ_2} the transition $\text{CO}_2^{(001)} - \text{CO}_2^{(020)}$,

$$\bar{n} = \sum \exp(-\theta_{(001)}/T), \quad \bar{n}_1 = \sum \exp(-\theta_{(100)}/T), \quad (4)$$

$$\bar{n}_2 = \sum \exp(-\theta_{(020)}/T),$$

with the initial conditions $T=T_0$ for $t=0$, and $n=\bar{n}$ for $T=T_0$, T_0 is the temperature of the gas outside the beam of radiation; Σ^{-1} is the partition function; $\theta_{(100)}$, $\theta_{(020)}$, and $\theta_{(001)}$ are the corresponding characteristic temperatures of the levels; τ_0 is the heat removal time; $\tau_{pj} = h\nu_j / \omega_j I$ is the pumping time of the combined mode and is defined in terms of the interaction cross-section σ_j and the radiation flux density I ; and, A is a constant, equal to 1000K for the atmosphere. The time interval over which the redistribution of the population of levels in the molecules occurs is much shorter than the characteristic heating time of the gas, and for this reason in studying the thermal explosion phenomenon the system of equations (3) can be reduced to one equation:

$$\frac{dT}{dt} = \Delta Q^+ - \Delta Q^- \quad (5)$$

$$\Delta Q^+ = -\frac{A}{\tau_{pj} + \tau \Sigma_j} (\bar{n}_j - \bar{n}); \quad \Delta Q^- = -\frac{1}{\tau_0} (T - T_0)$$

The possible thermal states of the atmospheric power CO₂ laser beam channel are given in Fig.2 and includes two stable states and one instable state.

Fig.2. Stable A, C and instable B states of the atmospheric power CO₂ laser beam channel for different values of the characteristic heat

removal time τ_o from the beam channel.

A thermal explosion occurs, when the value of the parameter:

$$\delta_1 = \frac{\tau_o A \theta_{(100)} \exp(-\theta_{(100)} / T_o)}{2 T_o (\tau_{\Sigma_1} + \tau_{p_1})} ;$$

for 10.6 μm radiation and
$$\delta_2 = \frac{\tau_o A \theta_{(020)} \exp(-\theta_{(020)} / T_o)}{2 T_o (\tau_{\Sigma_2} + \tau_{p_2})} ;$$

for 9.4 μm radiation exceeds the critical values $\delta_* = 1/e$. In the model under study ($A=1000\text{K}$, $\theta_{(100)} \approx \theta_{(020)} \approx 2000\text{K}$, $T_o=300\text{K}$) the threshold condition assumes the form $\tau_o / (\tau_p + \tau_{\Sigma}) \geq 13$. For this case the thermal instability of atmospheric power CO₂ - laser beam channel leads to a transition from stability state A to a stability state C.

In the case of a wide laser beam (for diameter $D > 10\text{cm}$) when heat removal can be neglected an adiabatic explosion develops in the atmosphere if the duration of the radiation pulse τ is longer than the explosion time interval τ_{ex} . The adiabatic heating time τ_{ex} can be found by solving Eq.4 with $1/\tau_o \approx 0$.

The adiabatic explosion time τ_{ex} in the atmosphere is given by:

$$\tau_{\text{ex}} = \tau_{p_1} \tau_{\Sigma_1} \left\{ \frac{T_o^2}{A \theta_{(100)}} \exp(\theta_{(100)} / T_o) \left(\frac{1}{\tau_{\Sigma_1}} + \frac{1}{\tau_{p_1}} \right) + \frac{1}{\tau_{\Sigma_1} + \tau_{p_1}} \right\} \quad (6)$$

for 10.6 μm radiation and

$$\tau_{\text{ex}} = \tau_{p_2} \tau_{\Sigma_2} \left\{ \frac{T_o^2}{A \theta_{(020)}} \exp(\theta_{(020)} / T_o) \left(\frac{1}{\tau_{\Sigma_2}} + \frac{1}{\tau_{p_2}} \right) + \frac{1}{\tau_{\Sigma_2} + \tau_{p_2}} \right\} \quad (7)$$

for 9.4 μm radiation.

For the field intensity $I \sim 10^3 \text{W/cm}^2$ of 10.6 μm and 9.4 μm radiation corresponds the pumping time $\tau_{p_j} \sim 10^{-3}$. The value $\tau_{\Sigma_j} \sim 10^{-3}$ is reached when the water vapor concentration in the atmosphere is about to several percent. For $\tau_{p_j} \sim \tau_{\Sigma_j} \sim 10^{-3}$ the adiabatic explosion time in the atmosphere is $\tau_{\text{ex}} \sim 10^{-1}$.

The heating of the atmospheric channels and absorption coefficient under the conditions of thermal instability of atmospheric CO₂ can be determined by solving the system (3). The result is present in Fig.3.

Fig.3. The results of calculations of temperature T and the absorption coefficient K_v of the CO₂ laser beam channel in the undercritical interaction regime 1 ($I=5 \cdot 10^3 \text{ W/s}^2$, $1/\tau_0=10^{-2} \text{ s}^{-1}$) and in the supercritical interaction regime 2 ($I=5 \cdot 10^3 \text{ W/s}^2$, $1/\tau_0=10^{-4} \text{ s}^{-1}$).

3.-Conclusion

The explosive absorption effect, manifested in terms of the thermal instability of a atmospheric air in the field of resonance radiation with $\lambda=10,6 \mu\text{m}$ or $\lambda=9,4 \mu\text{m}$, leads to significant (by an order of magnitude) drop in the transmission of the atmosphere and should be observed for a laser beam with a large diameter propagating through the atmosphere.

We note that this effect of thermal instability of CO₂ laser beam channel can occur for cw laser radiation and for pulse laser radiation when pulse repetition frequency $\Omega > 1/\tau_0$.

References

- 1 Usp. Phys. Nauk. 155, (4), 659, (1988).
- 2 A.N. Oraevskii, Khimiya Vys. Energ., 15, 462 (1981).
- 3 A.D. Margolin and V.M. Shmelev, Khim. Fizika, 5, 679 (1982).
- 4 A.S. Kaye and O.L. Naylor, Appl. Phys. Lett., 42, No.8, 641 (1983).