SOVIET PHYSICS JETP VOLUME 35, NUMBER 3 SEPTEMBER, 1972

Amplification Factor of Light in a $Co_2^+N_2^+He$ Mixture Expanding in a Supersonic Jet

G. V. Gembarzhevskiĭ, N. A. Generalov, G. I. Kozlov, and D. I. Roĭtenberg

Institute of Mechanics Problems, USSR Academy of Sciences

Submitted July 22, 1971

Zh. Eksp. Teor. Fiz. **62**, 844–847 (March, 1972)

The results of an experimental and theoretical investigation of the amplification factor of a CO_2+N_2+He mixture expanding in a supersonic jet located at the end of a shock tube are reported. Good agreement between the experimental data and results of the theoretical analysis is obtained.

THE general idea of producing inverted population in gases by an abrupt change in the temperature was discussed in[1,2]. The first indication of the possibility of obtaining inverted population by adiabatic expansion of a $CO_2 + N_2$ gas mixture is contained in[3,4]. Lasing by gas expansion through a nozzle and a slit was observed experimentally in[5,6]. The amplification of the medium was investigated at temperatures not exceeding 1800°K[6-8].

In the present study, we determined the gain of the mixture of 10% CO_2 + 40% N_2 + 50% He expanding supersonically in a wide range of stagnation temperatures, T_0 = 800–3100°K, and compared the results with the calculated values obtained on the basis of the method proposed by us earlier[9]. A comparison of the experimental and theoretical data on the expansion coefficient in the temperature interval 800–900°K was made also by Lee and Gowen[8], who referred, however, to unpublished calculations by Anderson.

The experimental study of the gain was made with a setup shown schematically in Fig. 1. It consisted of an aerodynamic shock tube and an optical system with the aid of which the gain was measured.

The aerodynamic shock tube, a detailed description of which is given in[10], consisted of a shock tube proper 1, a receiver 2, and a supersonic nozzle 3 placed at the end of the shock tube. Prior to the experiment, the entry into the nozzle was covered with a membrane, making it possible to pump out the shock tube and the receiver separately to specified values of the pressure. After the evacuation, the low-pressure chamber of the shock tube was filled in all experiments with the mixture at the same initial pressure, P_1 = 0.22 atm.

When the shock wave was reflected from the end of the shock tube, the membrane was broken and the investigated gas mixture, heated by the reflected shock wave, expanded through the supersonic nozzle into the receiver. The nozzle had a complex configuration, with the Laval nozzle going over at a certain distance from the critical section into a tube with a conical profile and a small aperture angle.

The gain of the investigated gas mixture was measured in the following manner. Continuous infrared radiation (λ = 10.6 μ) from CO_2 laser 4 passed through sighting windows of KCl perpendicular to the gas-mixture stream and was gathered with the aid of lens 6 on to the receiver 7, comprising a Ge-Au photoresistor. A diaphragm 9 placed ahead of the lens limited the intensity of the spontaneous emission of the investigated mixture. The signal from the receiver was fed to oscilloscope 10. The minimum measured gain in our experiments was determined by the receiver noise and by the laser-radiation fluctuations, and amounted to 0.1% over a path length of 6 cm. To eliminate the influence of the instability of the IR radiation on the measurement accuracy, some of the energy was diverted from the beam with the aid of a plane-parallel plate 8, was interrupted by an obturator 5, and was registered by the Ge-Au receiver 7, the signal from which was then fed to the oscilloscope 10.

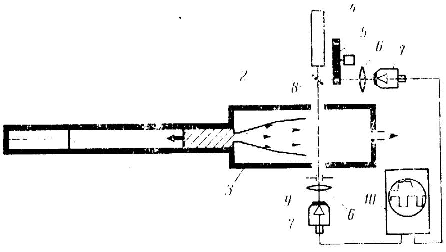

FIG. 1

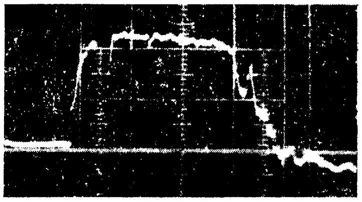

FIG. 2

A typical gain oscillogram is shown in Fig. 2. In this experiment, the stagnation temperature and pressure of the gas behind the front of the reflected shock wave were 1750°K and 15 atm, and the gain K was close to 3×10^{-3} cm^{-1}. It is seen from Fig. 2 that the gain of the mixture remains practically constant for 1.5 msec (the scale is 0.5 msec/div), after which it decreases sharply and turns into absorption. The typical form of the oscillograms in all these experiments remained approximately the same, with the exception of the pulse duration, which decreased significantly with increasing shock-wave velocity.

To eliminate the influence of the spontaneous radiation on the value of K, we performed a series of measurements of its intensity. In these experiments, the radiation registration system was the same as before, with only the CO_2 laser left out. The experiments have shown that spontaneous emission in the infrared region

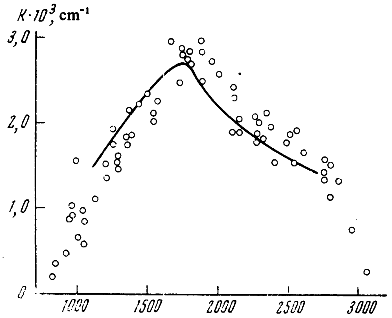

FIG. 3

can be registered only at $T_0 > 2000$°K. Thus, for example, at $T_0 \sim 2200$°K, under conditions of our experiments, the intensity of the spontaneous emission is less than 5% of the intensity of the stimulated emission, and reaches 30% at $T_0 \sim 3000$°K.

The results of the experimental investigation of the gain of the gas medium as a function of the initial temperature T_0 are shown in Fig. 3 (the stagnation-temperature values shown on the plots were calculated with allowance for excitation and dissociation of the components). For the nozzle geometry and mixture composition chosen by us (10% CO_2 + 40% N_2 + 50% He), the quantity K goes through a maximum at $T_0 \sim 1800$°K. The maximum value of the gain is approximately 3×10^{-3} cm^{-1}. The reason for such behavior of the gain is as follows. When the temperature is increased from 800 to 1800°K, the populations of the asymmetrical valent and deformation oscillations increase, and their difference also increases. With further increase of the temperature, the rate of deactivation of the asymmetrical valent oscillation decreases considerably, as a result of which the population levels of this type of oscillation does not increase as rapidly as that of the deformation type. This leads to a decrease of K in the region $T_0 > 1800$°K. At $T_0 > 2700$°K, a still greater decrease of the gain is observed, connected simultaneously with an increase in the temperature and in the degree of dissociation α of the CO_2 molecule. Thus, for example, whereas α amounts to approximately 20% At $T_0 \sim 2700$°K, it reaches 40% at $T_0 = 3100$°K. In the temperature interval $T_0 = 3000-4000$°K, the gain remains approximately constant (3×10^{-4} cm^{-1}).

It is of fundamental interest to compare the experimental values of K with the calculated ones. In[9] we proposed a procedure for determining the level populations of different oscillation modes of the CO_2 molecule when mixed with He and N_2 and escaping from a nozzle. In the present study, this procedure was used as applied to the experimental conditions. The gain of the medium was calculated by the formula[11]

$$K(\nu) = \frac{c^2 A_{vJ}^{v'J'}}{8\pi^2 (\nu_{vJ}^{v'J'})^2} \times \left(\frac{n_{v'J'}}{g_{J'}} - \frac{n_{vJ}}{g_J}\right) S(\nu - \nu_0)$$

where $S(\nu - \nu_0)$ is the form factor of the emission line, $A_{vJ}^{v'J'}$ is the Einstein coefficient for spontaneous emission, $n_{v'J'}$ and n_{vJ} are the populations of the vibrational-rotational levels, $g_{J'}$ and g_J are statistical weights, and $\nu_{vJ}^{v'J'}$ is the transition frequency. The rotational temperature of the CO_2 was assumed to equal the translational temperature during the course of the mixture expansion.

The estimates have shown that under the conditions of our experiments, the function $S(\nu - \nu_0)$ was determined simultaneously by the Doppler and collision broadenings. We therefore used the Voight functions to determine the emission line widths.

The gain was calculated for the line center ($\nu = \nu_0$), under the assumption that $A_{vJ}^{v'J'} = 0.2$ sec^{-1}. For comparison with the experimental data, the results of these calculations are represented by the continuous curve in Fig. 3. It follows from the analysis of Fig. 3 that the experimental and theoretical values of the gain agree well not only in the character of the temperature dependence, but also in absolute value.

Thus, our experimental investigation of the gain of the $CO_2 + N_2 + He$ mixture confirms the correctness of the fundamental physical premises on which the theoretical analysis in[9] is based. This enables us to calculate theoretically, with sufficient reliability, the optimal conditions for obtaining the maximum gain of $CO_2 + N_2 + He$ mixtures.

It should be noted in conclusion that inasmuch as the gain K is determined, in addition to other factors, by the population of the vibrational levels of the molecules and by the total density of the particles, and under the conditions of our experiments these two parameters depend on the intensity of the shock wave and consequently on the gas temperature, it follows that for a comparison of the data of others it is desirable to use the amplification cross section σ(cm^2), i.e., the gain per gas particle. In our experiments, the gas density in the region of the nozzle, where the gain of the medium was investigated (in the range $T_0 = 800-2500$°K), was determined approximately by the expression

$$N \approx 3.35 \cdot 10^{17} \left(1 + 0.36\,\mathrm{th}\frac{T_0 - 1850}{600}\right) \quad [\mathrm{cm}^{-3}].$$

Therefore the $\sigma(\nu)$ curve is similar in shape to the $K(\nu)$ curve. The difference lies only in the fact that the $\sigma(\nu)$ curve has a more clearly pronounced maximum, which is shifted somewhat towards lower temperatures.

The authors are deeply grateful to Yu. P. Raĭzer for a discussion of the results

---

[1] N. G. Basov and A. N. Oraevskiĭ, Zh. Eksp. Teor. Fiz. **44**, 1742 (1963) [Sov. Phys. JETP **17**, 1771 (1963)].

[2] I. R. Hurle and A. Hertzberg, Phys. Fluids **8**, 1601 (1965).

[3] V. K. Konyukhov and A. M. Prokhorov, Author's Certificate No. 223,954, priority Nov. 19, 1966, Byull. Izobr. No. 25, 1968.

[4] V. K. Konyukhov and A. M. Prokhorov, Zh. Eksp. Teor. Fiz., Pis'ma Red. **3**, 436 (1966) [JETP Lett. **3**, 286 (1966)].

[5] D. M. Kuehn and D. J. Monson, Appl. Phys. Lett. **16**, 48 (1970).

[6] A. P. Dronov, A. S. D'yakov, E. M. Kudryavtsev, and N. N. Sobolev, Zh. Eksp. Teor. Fiz., Pis'ma Red. **11**, 516 (1970) [JETP Lett. **11**, 353 (1970)].

[7] V. K. Konyukhov, I. V. Matrosov, A. M. Prokhorov, D. T. Shalunov, and N. N. Shirokov, Zh. Eksp. Teor. Fiz., Pis'ma Red. **10**, 84 (1969) [JETP Lett. **10**, 53 (1969)].

[8] G. Lee and F. E. Gowen, Appl. Phys. Lett. **18**, 237 (1971).

[9] N. A. Generalov, G. I. Kozlov, and I. K. Selezneva, Preprint of the Institute of the Problems of Mechanics, Acad. Sci. USSR, No. 2, 1971.

[10] G. I. Kozlov, Yu. P. Raĭzer, and D. I. Roĭtenburg, Prikl. Mat. Teor. Fiz. (1), 140 (1968).

[11] C. K. N. Patel, Phys. Rev. A (1964–1965) **136**, 1187 (1964).

Translated by J. G. Adashko
101