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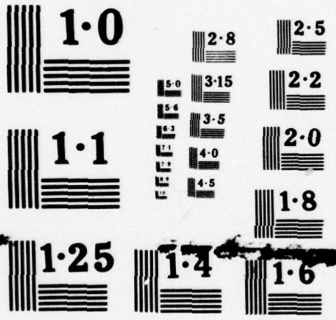
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FOREIGN TECHNOLOGY DIVISION

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by

P. Wolanski

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Gas Dynamic Lasers Pumped by Combustion

by

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Abstract: The gas dynamic lasers are discussed, in which the combustion processes are used for thermal pumping. The energy system of CO_2- N_2 molecules and the population inversion mechanism in the supersonic nozzle are discussed. Lasers of existing types are analyzed in their optimum operating conditions, and the prospects for the future progress.

Introduction

The possibility of creation of the population inversion in the rapidly expanding gas was first studied by Hurtle and Hertzberg (13). They studied the electron level inversion in the expanding xenon. The attempts for the experimental confirmation of their concept, however, was unsuccessful. Shortly after Basov (5), (6), and Konyukov (14) showed, that the expansion of heated CO_2 - N_2 mixture in the supersonic nozzle can cause the population inversion of the oscillalary levels in the CO_2 molecule. The laser acting on this principle is called the thermally pumped gas dynamic laser. It differs from the electrically (20) or chemically (12) pumped lasers in which the gas flow is utilized for carrying the lost energy, temperature and mixing control, or to remove the reaction products. In thermally pumped gas dynamic lasers, the expansion (in a continuous flow) of hot gas mixture is primarily used for obtaining the population inversion.

The most common thermally pumped gas-dynamic lasers are the one using the CO_2 - N_2 mixture, with addition of helium or water vapor (7), (11), (15), (18), (20) through (24). There are also the gas-dynamic lasers using NO_2 - N_2 - He mixture (7).

There are several ways of heating the gas mixture. In laboratory measurements, the most common method is to use the simple shock tubes, in which one easily obtains high temperature and pressure. The disadvantage of these devices is the short work time. In the continuous action lasers, the required medium temperature is obtained using the arc heaters (2), (7), (17) or by the combustion of certain fuels (11), (12), (17), (22) through (24).

In this paper we will discuss the gas-dynamic lasers using the combustion for creating the gas mixture and thermodynamic pumping. For convenience, in the remainder of this paper, we will refer to these lasers as the gas-dynamic lasers.

1. The Analysis of Gas-Dynamic Laser Action

In the working mixture of the gas dynamic laser, the CO_2 molecules play an active role. They are linearly symmetric. In the ground level, the two oxygen atoms are equally distant from the center carbon atom. The possible oscillatory modes of such a molecule are shown in Fig 1. For the symmetric oscillations (Fig 1.b) the oxygen atoms move symmetrically along the molecule axis. In the case of deformed oscillations (Fig 1. c) the atoms move perpendicular to the axis. This type of oscillations can be decomposed into two mutually perpendicular oscillatory components. For the asymmetric oscillations, the atoms move asymmetrically along the axis. For these three types (or modes) of oscillatory motions, labelled ν_1, ν_2, ν_3, there are assigned three energy quantum numbers p, q, r and the momentum quantum number ~~γ~~ l, determining the type of deformed oscillatory mode. The molecule state is described by the set of these numbers in a following manner (p, $q^{\pm l}$, r). For example, if the molecule has only one type of oscillation in ν_3 mode, its state is described by ($00^0 1$).

Fig. 2 shows the oscillatory levels of CO_2 and N_2 molecules with the most interesting transitions in this system (21). The nitrogen as a simple, diatomic molecule, is characterized by a single type of oscillatory motion.

In the gas dynamic laser there are many possible energy transfers between molecules and within the CO_2 molecule itself. Nearly resonance energy exchange takes place between the first oscillatory energy level of nitrogen and the first asymmetric oscillatory level of carbon dioxide. This exchange can be expressed by the relation:

$$CO_2(00^00) + N_2(1) \rightleftarrows CO_2(00^01) + N_2(0) - 18\ \text{cm}^{-1}$$

The energy from the levels CO_2 ($00^0 1$) and $N_2(1)$ can be lost by the collisons with the not excited CO_2 and N_2 molecules, and with the helium and water vapor molecules which, for simplicity, are not included in the scheme. Freeing the lower energy levels of CO_2 (ν_1, ν_2) takes place through the collisions with all components of the mixture. It is the fastest, however, in the collisions with the water vapor molecules.

The laser emission takes place as a result of the transition from the first asymmetric oscillatory level ($00^0 1$) (known as the upper laser level) to the first symmetric oscillatory level ($10^0 0$) (known also as the lower laser level). In certain conditions, the laser emission is also possible for the ($00^0 1$) $\longrightarrow$ ($02^0 0$) transition.

The condition for the gas dynamic laser action is the rapid expansion of the hot laser working mixture in the supersonic nozzle. The result of this process is the lowering of temperature and pressure in the time interval shorter than the relaxation time of the CO_2 (00^01) and N_2 (1) levels. Simultaneously, due to the helium and water vapor admixture, the relaxation of the lower working levels is taking place, in about the same or shorter time interval than the time of the mixture flow through the nozzle. As a result of rapid expansion, the upper laser levels are unable to follow the rapid temperature and pressure change and become "frozen". Since the relaxation time for these levels is long, their population will remain unchanged even at considerable distances from the nozzle.

The work principle of the gas dynamic laser is shown in Fig 3. (12). The working mixture composed of 0.075 CO_2, 0.913 N_2, 0.012 H_2O at the temperature of 1400°K is placed in the container under the pressure of 17 ata. The expansion takes place in the flat nozzle with the critical cross section height h = 0.8 mm, and the ratio of the exhaust to the critical cross section $A/A^* = 14$. At the nozzle exhaust the Mach number = 4, the pressure is about 0.1 ata, and the temperature is close to the ambient temperature.

Fig 3 b. illustrates the energy distribution of the laser mixture into different degrees of freedom, in the different areas of supersonic nozzle. In the stagnation area, most of the energy is concentrated in the translational and rotational degrees of freedom. Only about 10% of the energy is in the oscillatory state. During the expansion in the supersonic nozzle, the translational and relational energy converts directly into the flow kinetic energy.

If the oscillatory energy was in the equilibrium state, it would then dissipate in the nozzle. **Sufficiently** rapid expansion causes that the oscillatory energy is "frozen" during the flow, and its oscillatory temperature is typical for a flow in the nozzle's critical cross section.

Considering the inversion in the discussed flow (Fig 3 c), one can see that the population of the lower levels exceeds the population of the higher levels in the stagnation area (which is typical for the gas in the equilibrium state). At the initial expansion period, the population of the higher laser levels somewhat decreases, but it stabilizes at the short distance behind the nozzle's critical cross section. On the other hand, the population of the lower laser levels drastically decreases and al~~s~~most disappears at the short distance from the nozzle's critical cross section. The water vapor or helium, frees the energy from the lower laser levels. The population of the upper laser levels ~~of~~ at the nozzle exhaust is typical for the gas at the temperature a little lower than the stagnation temperature, and the population of the lower laser levels is typical for the temperature of the gas flow at the nozzle. The inversion state created at the nozzle exit remains in the laser channel for a distance up to 1 meter.

Due to the relative high density of gas mixture flow in the nozzle, it is possible to obtain very high power outputs from the unit volume of flow. The amount of useful energy depends on the energy stored in the excited nitrogen molecules and in the asymmetric oscillations of carbon dioxide. The maximum possible energy output for the laser transition can be expressed by the following **relation** (assuming that the upper levels are frozen in amounts characteristic for the stagnation temperature (12)).

$$E_{max} = h\nu[\exp(3380/T_{st}) - 1]^{-1}$$

where: h - Planck's constant

ν - frequency

T_{st} - stagnation temperature.

For the mixture of 0.1 CO_2 and 0.9 N_2, heated to 1400°K, this energy is 35 kJ per kilogram of the medium. Of course, this energy cannot be completely converted into radiation. In the existing systems it is possible to utilize only 15% of this energy (9). It is possible, that in a short time this amount can be doubled or tripled. This will depend on the design improvements to the gas-dynamic lasers.

The largest energy losses are taking place in the nozzle, due to incomplete "freezing" of oscillatory energy and the negative effect of the layer adjacent to the wall (smearing effect). In order to minimize these losses, the nozzle design must be such, that at its critical cross section, the freezing of upper laser levels is very rapid. This can be done by designing the nozzle with small critical cross section. In such a nozzle the gas quickly reaches the exit parameters.

In Fig 4 there are shown nozzle types used most often in gas dynamic lasers (11). Flat single slit nozzle, with a resonator axis parallel to the critical cross section slit (Fig 4 a) is relatively long. The studies showed, that this nozzle shape doesn't lead to fast "freezing" of the upper laser levels and it causes the formation of very extensive wall layer. The turbulent wall layer is optically very inhomogenous and causes perturbations in the resonator work. The nozzle array, in which the slits are perpendicular to the resonator axis (Fig 4 b) is much more useful. In this system the wall layer is much smaller. The turbulent traces, formed behind the nozzle edge, have very small optical thickness and disturb the resonator work to a much smaller degree.

In the laser cavity, the majority of energy is stored in nitrogen oscillations. This energy must be transferred to the carbon dioxide during the flow through the resonator. The length of the resonator mirrors should be proportional to the flow velocity, and inversely proportional to the rate of energy transfer to the carbon dioxide. The length of the resonator mirror calculated according to the above rule (11) has too low a value, since the rate of energy transfer N_2 (1) $\longrightarrow CO_2$ (00^01) is in the reality limited by the rate of energy release from the lower laser levels.

2. Modelling Studies

The goal of the gas dynamic lasers modelling, is the determination of the optimal working parameters, and the verification of components efficiency (nozzle, resonator etc.) These studies are conducted with the use of shock tubes (4), (10), (11), (12), (16) or small devices of continuous action (4), (7), (18). The shock tubes, however, became the basic tool used in the gas dynamic laser studies, since they are simple to use and enable to obtain any parameters.

The diagram of the shock tube used for the gas-dynamic laser studies, is shown in Fig 5. The working mixture, after compression and heating (by a shock wave), flows through the nozzle to the measurement zone. During the quasistationary flow (usually lasting a few miliseconds) it is possible to measure the amplification factor, which determines the population inversion ratio in the gas flow.

For the measurements of amplification factor the additional low power laser is used. The laser beam (of known input power p_o) passes through the gas-dynamic laser cavity, where it is amplified. Measuring the power p of the output beam, one can determine the amplification factor (for the condition far from saturation). using the relation:

$$\alpha = \frac{p - p_0}{pL}$$

where: α - amplification factor

L - cavity width

The amplification factor is studied in order to optimize the laser working parameters,

3. Gas Dynamic Laser Pumped by Combustion

The gas dynamic lasers, in which the combustion is used for pumping and forming the working mixture, can be divided into two basic groups: pulsed lasers and the continuous wave lasers.

3. 1. Pulsed Lasers

The diagram of the gas dynamic pulsed laser is shown in Fig 6a. The combustion chamber is filled with the explosive mixture with the addition of nitrogen. The mixture contents is chosen in such a way, that after the combustion, the chamber is filled with the combustion products of proper composition, pressure and temperature (for example compositions given in Table 1.). After the parameters of created mixture equalize, the electromagnetic valve is open, or the membrane (acting as a valve) is broken. The combustion chamber and the nozzle become joined.

The working mixture, after expansion in the supersonic nozzle (where the population inversion takes place), flows through the resonator, in which the laser action takes place. The vacuum container is placed behind the resonator.

Some of the gas-dynamic pulsed lasers are equipped with the electromagnetic valves, allowing the repetition of the laser action in a short time intervals. The volume of combustion chamber is several liters, which in conjunction with the large vacuum container allows the laser action time on the order of a few tenths of the second.

The power obtained from the pulsed laser is becoming larger. Tulip (23) obtained powers reaching 100W. He studied the influence of different fuels on the laser action. The summary of his results are given in Table 1).

The gas-dynamic pulsed laser (24) fueled by the explosive mixture of CO, H_2, O_2, N_2, radiates about 30 J of energy in 0.3 sec. In the initial phase, the power reaches 200W. The main advantage of the gas-dynamic pulsed lasers is their simple design and simplicity in operation. They do not require the expensive cooling systems. The disadvantage is their short work time and the necessity of installing the large vacuum container. But they may be successfully used where the pulsed work is required. They are also used as the diagnostic tools, which allows, in their quasistationary range, to optimize the parameters of the continuous wave lasers.

3.2 Continuous Wave Lasers

The continuous **wave** gas-dynamic lasers may be divided into two subgroups. The first one, includes the small devices (used mainly for studies), working with the large vacuum chamber and the vacuum pump. The second subgroup includes the high power lasers, equipped with the supersonic-subsonic diffusers, eliminating the need for the vacuum chambers and pumps.

The diagram of the continuous wave gas-dynamic laser is shown in Fig 6b. The fuel is burned with the air in the combustion chamber in such proportions, as to obtain the laser mixture with the proper content and temperature. The fuel (similarly as with the pulsed lasers) is the carbon monoxide with the addition of hydrogen or other carbohydrates. One can also use cyanogen (C_2N_2) with the carbohydrates, or carbohydrates alone. The combustion process takes place under the pressure of several atmospheres. To form the final laser mixture, the second chamber is used, in which the combustion products are mixed with nitrogen.

Minzer (18) using the small c.w. gas dynamic laser, measured the dependence of the amplification factor on the molar contents of combustion products. The Minzer results are given on Fig 7. The maximum amplification and power on the order of 50 W, was obtained for the mixture of 0.27 CO_2, 0.70 N_2, 0.03 H_2O. He also conducted the experiments on burning the liquid fuels (ethylene), and studying their usefulness for the gas dynamic lasers. The best results, however, he obtained using the carbon monoxide and carbohydrates.

The second gas dynamic laser subgroup includes the high power lasers: from few to several tens of kilowatts. Their design differs from the other lasers in the respect that instead of the vacuum chamber, the supersonic - subsonic diffuser is used, which exhausts the gases directly to the atmosphere, while maintaining the low pressure inside the laser cavity.

For the parameters of the working mixture (Fig 3), obtained from burning CO with additional H_2, Gerry (12) obtained 6 kW of power, with the multiopening stable resonator system; using the astable resonator he obtained 2 kW of power (11). Using the similar device, one obtained 60 kW of power with the stable resonator, and the medium mass ten times as high (14 kg/s). This same device, allowing for the mode control of laser beam, gives the continuous power of 30 kW.

The important element of the gas dynamic laser, is the resonator. The schematic drawings of used resonators are shown in Fig 8. (12).

The most often used resonator in the gas-dynamic laser, is the stable resonator (Fig 8a.), characterized by a simple construction and allowing to obtain the high radiative power. In this system, the better results could be obtained by using the mirrors of variable transmission along their length (8). The stable resonators usually work in a multimode system (11), (12), in which it is not possible to obtain beams of small divergence. This fault can be eliminated by use of astable resonators

(Figs 8b. and 8c.). These resonators can have complex mirror shapes (9), (11), (12), or mirror systems with rather simple shapes, but with the steering laser. The electrically pumped steering laser (Fig 8c.), with the high mode selection, allows for obtaining the high monochromacity and low beam divergence in the astable resonators.

The loss analysis **of** the gas-dynamic laser, performed by Gerry (11, 12), allows the conclusion that the laser efficiency can be improved in the near future, by the careful design of all its components. The greatest care and attention should be given to the nozzle and resonator design.

The theoretical analysis by Anderson (25) predicts that the next generation of gas-dynamic lasers will work at the elevated temperature and higher concentration of water vapor. The higher temperature allows the many fold increase in energy which can be converted into the laser radiation. At the temperatures exceeding 2000° K the negative effect of dissociation and deactivation of the laser levels becomes **noticeable. The** dependence between energy amount from the laser transitions and the gas mixture temperature is shown in Fig 9.

Conclusion

Use of the combustion processes for creation and pumping of the working mixture in gas dynamic lasers, constitutes the considerable progress in the technology of high power laser radiation. These lasers were developed rapidly. Despite their **relatively** low efficieny as compared with the electrically pumped lasers (15) the development was fast. The reason is the simplicity of the design and high efficiency of heating the working mixture (combustion products). Such efficiency is not possible in the gas-dynamic lasers in which the working mixture is heated by the arc. Such lasers can be used, however, in the systems with the selective pumping of the medium. In these conditions the higher efficiencies and power **densities** are obtained (16). The necessity of using the arc heaters (characterized with the low gas heating efficiency) did not allow **achieving** high power in c.w. mode. The lasers with the arc heaters additionally require complex power supply system, while the gas dynamic lasers pumped by combustion have simple combustion chambers, and are fueled with common and inexpensive gas fuels. The largest of existing gas dynamic lasers, fueled by a gas mixture of carbon monoxide and methane, achieves the power of 60 kW.

The goal of the continuing work on these lasers is to increase their power and efficiency, and to lower the size and increase the working time. The simple design of these devices and ease of the operation are **conductive** to the new development work. It appears that the next few years will be very important period in the development of the knowleege on gas dynamic lasers.

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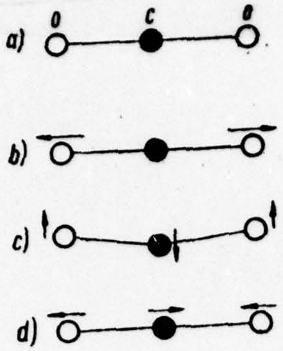

Fig 1. Types of the linear oscillations of carbon dioxide molecule

a) diagram of atoms layout,

b) symmetric oscillations, the atoms move along the molecule axis,

c) deformed oscillations, the atoms move perpendicular to the molecule axis

d) asymmetric oscillations, the atoms move asymmetrically along the axis

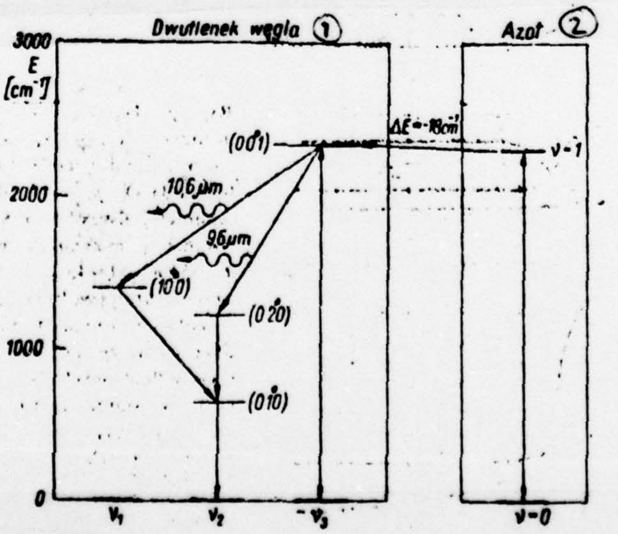

Fig 2. Diagram of the lower oscillatory energy levels of CO_2 and N_2 molecules

1. - carbon dioxide

2. - nitrogen

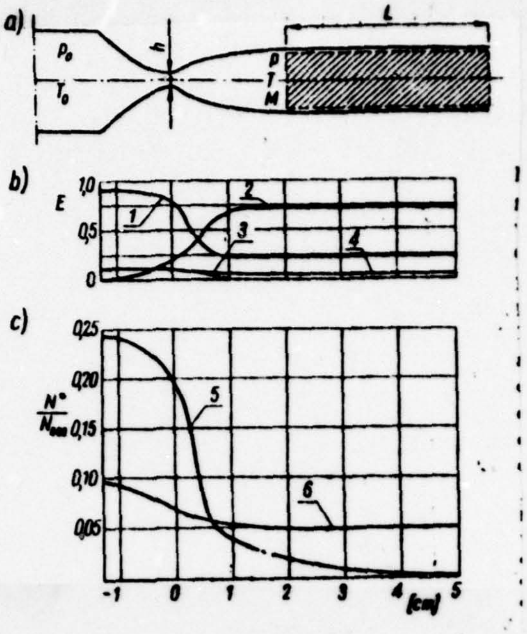

Fig 3. Typical work condition of the gas dynamic laser (initial mixture parameters: 0.075 CO_2, 0.913 N_2, 0.012 H_2O, p_0= 17 ata, T_0 = 1400° K, nozzle parameters: h = 0.8 mm, A/A^* = 14, mixture parameters of the nozzle exhaust: T = 354° K, M = 4.02, p = 0.066 ata)

a) nozzle outline, b) energy distribution into different degrees of freedom as a function of nozzle length, c) the ratio of the number of excited molecules N^* to the number N ~~(000)~~ (00^00) of molecules in the ground state.

1 - rotational - translational energy,

2 - kinetic energy of the flow,

3 - oscillatory energy in the equilibrium flow,

4 - oscillatory energy in the frozen state,

5 - molecules pumped to the level $(10^0 0)$,

6 - molecules pumped to the level $(00^0 1)$.

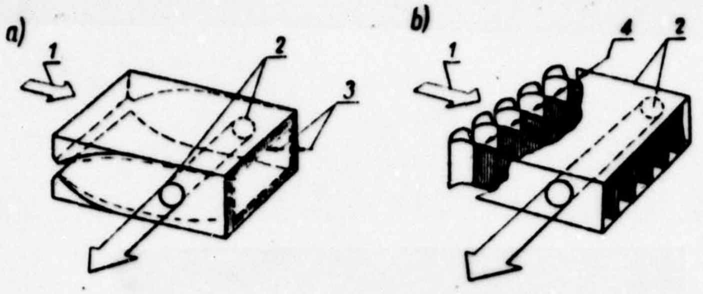

Fig 4. Schematic diagram of the supersonic nozzles used in the gas dynamic lasers.

a) simple nozzle

b) multislit nozzle

1 - direction of flow

2 - resonator

3 - wall layer

4 - turbulence formed at the nozzle edge

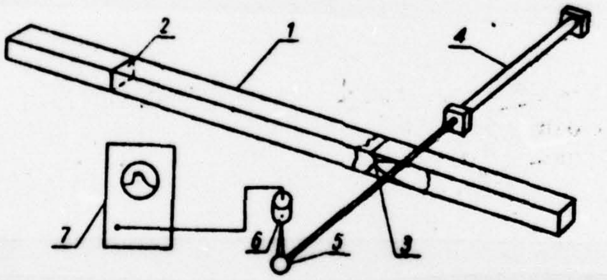

Fig 5. Schematic diagram of the system measuring the amplification factor using the shock tube.

1 - shock tube,

2 - membrane

3 - nozzle

4 - auxiliary CO_2 - N_2 - Me laser

5 - mirror

6 - power meter

7 - oscilloscope

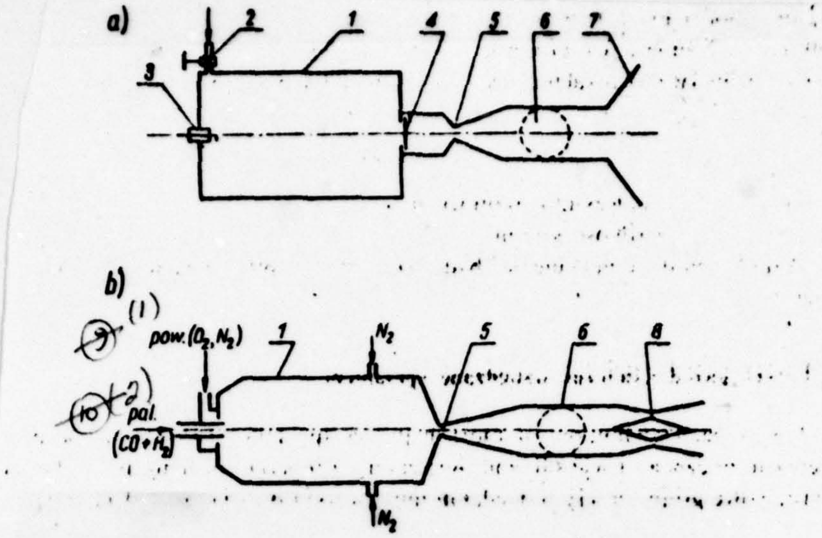

Fig 6. Basic types of combustion gas dynamic lasers

a) diagram of the pulsed laser

b) continuous wave laser

1 - combustion chamber

2 - fuel inlet

3 - ignitor

4 - valve

5 - nozzle

6 - laser cavity

7 - exhaust diffuser

8- supersonic - subsonic diffuser ,

Key (1) ~~9~~ - air

(2) ~~10~~ - fuel

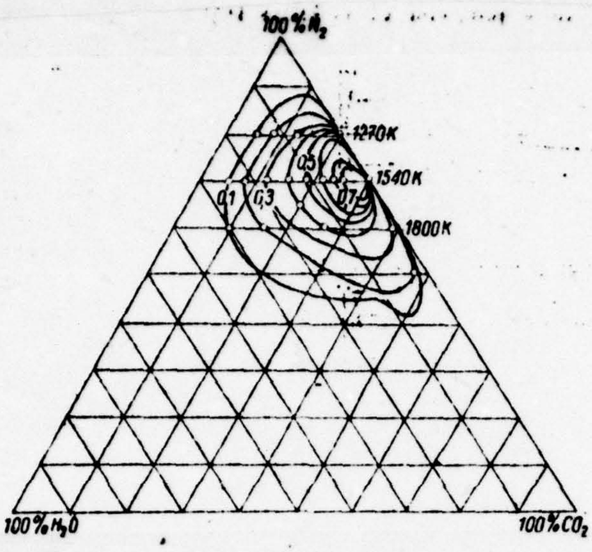

Fig 7. The results of the measurements of amplification factor as a function of molar content of combustion products (amplification factor is determined at the conditions for from saturation during P (20) transition and for the consumption of 0.6 mols/sec)

Rodzaj paliwa ①	Skład spalin ② $N_2-CO_2-H_2O$	Moc maksymalna [W] ③
Gaz ziemny ④	0,80 – 0,066 – 0,134	50
Acetylen ⑤	0,82 – 0,12 – 0,060	70
Propan ⑥	0,80 – 0,085 – 0,115	100

Table 1. The comparison of the parameters of pulsed gas dynamic laser fueled with different fuel gases

1 - fuel

2 - combustion gas composition

3 - maximum power

4 - natural gas

5 - acetylene

6 - propane

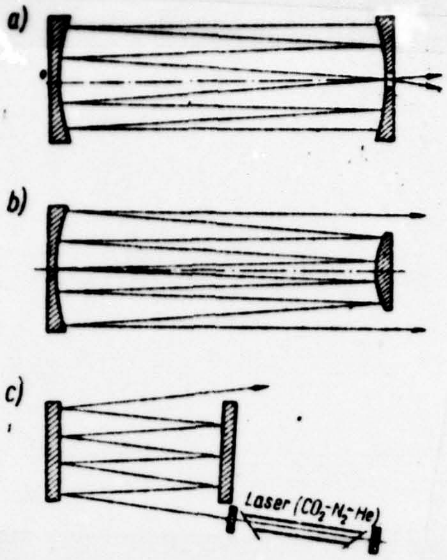

Fig 8. Schematic diagrams of the resonations

a) stable resonator

b) astable resonator

c) astable resonator with a steering laser

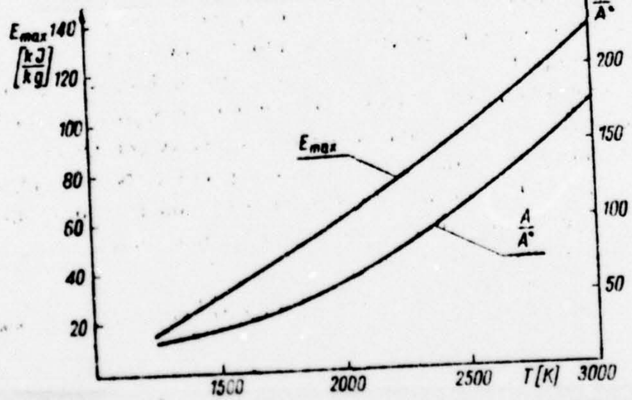

Fig 9. Dependence of the maximum laser transiton energy as the mixture temperature before the nozzle, at the optimal ratio of the nozzle exit cross section A to its critical cross section A* (mixture composition: 0.07 CO_2, 0.895 N_2, 0.035 H_2O, P_0 = 30 ata)

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