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Abstract

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HIGH-PRESSURE CHEMICAL LASERS AND LIGHT-STIMULATED CHEMICAL REACTIONS

After the fundamental works $^{(1-3)}$, laser physics developed rapidly and became a most topical field of science with important applications in technology. In constructing a laser, the principal problem is to create an inverse population of the energy levels of the system. Usually this is achieved by "pumping"the system with light, a beam of particles, etc. In the future, with the mass use of lasers, the question of their economy, efficiency, and power will arise; from this standpoint the above-mentioned pumping may in many cases prove inexpedient. Thus, the average power of the laser beam is always less than that of the pump beam. The pump energy is obtained by burning fuel at a power station and subsequently converting the electric power into pump light with large losses. Meanwhile, the fuel itself is a ready-made substance with an inverse population of energy levels. Such is any substance capable of an exothermic chemical reaction. Theoretical investigations carried out by us have shown the possibility and expediency of directly converting the chemical energy of fuel into the light energy of a laser beam. In this case powers and efficiencies can be obtained that are greater than those of present-day chemical and other lasers.

Speaking of chemical lasers, we have in mind only those that operate without pumping, exclusively at the expense of the energy of a chemical reaction. In known lasers of this type $^{(4-10)}$ there are two stages of the process: 1) an ordinary chemical reaction, proceeding without the participation of stimulated light, whose products are excited molecules; 2) stimulated emission of the excited molecules, proceeding without chemical reaction. The first of these stages limits the rate and power of the whole laser process by the rate and power of an ordinary chemical reaction; it is accompanied by heat release, leading to energy losses and destruction of the working setup at high powers.

In the present work we consider the possibility of creating a laser of another type, in which the stimulated phototransition of electrons occurs at the moment of contact of two unexcited reacting gas molecules. This radiative transition of electrons, changing the interatomic forces, i.e., the chemical bonds, itself is the elementary act of the chemical reaction. Thus, stage 1) with its disadvantages noted above, as well as stage 2), is absent.

Fig. 1

Figure 1: Fig. 1

For estimates let us suppose that there exists a region of mutual configurations of a pair of molecules in which the molecules are regarded as being in contact and the spontaneous phototransition of electrons has a significant probability $p \sim 10^6$ s^{-1}, while in the rest of configuration space $p = 0$. Let ω_m be the position of the maximum of the spontaneous-emission band, and $\Delta\omega$ its effective width. The number of simultaneously contacting pairs of molecules in 1 cm^3 is equal to $\upsilon n_1 n_2$, where n_1 and n_2 are the concentrations of the reacting molecules, and we shall take the coefficient υ to be of the order of 10^{-23} cm^3. The number of optical modes in 1 cm^3 with frequencies in the interval $\Delta\omega$ is equal to $\omega_m^2 \Delta\omega / \pi^2 c^3$, where c is the speed of light.

In a gas with an inverted population of levels, the intensity of the light wave increases in space according to the law $I(x) = I_0 e^{\alpha x}$. Applying the usual theory of lasers, for the gain coefficient α we obtain

$$\alpha \sim \pi^2 c^2 p \upsilon n_1 n_2 \mid \omega_m^2 \Delta\omega. \tag{1}$$

Assuming $n_1 = n_2 = n = 10^9$ cm^{-3}, $\Delta\omega = 0.01\,\omega_m$, $\omega_m = 3 \cdot 10^{15}$ sec^{-1}, and using the values of p and υ given above, we obtain $\alpha \sim 0.03$ cm^{-1}. It is assumed that the reaction products are removed sufficiently rapidly, or that their concentration is negligibly small at the beginning of the pulsed reaction. The obtained value of α is quite sufficient for creating a laser with mirrors or without mirrors, if the linear dimensions of the volume filled with gas are sufficiently large. However, α can be further increased by increasing the concentration n.

Fig. 1

If the loss of the initial molecules is not replenished, the reaction will be pulsed in character and will cease when approximately half of the initial number of molecules n has reacted. At the height of the reaction, the number of photons in the working mode will be of the order of $\frac{1}{4}n$ in 1 cm^3. During this period the rate of the stimulated chemical reaction (the number of elementary reaction events per 1 sec in 1 cm^3) is $\frac{1}{4}n\alpha c = 2.5 \cdot 10^{27}$ cm^{-3} $\cdot$ sec^{-1}, and the light power released in 1 cm^3 is $\hbar\omega W \sim 7 \cdot 10^8$ W $\cdot$ cm^{-3}, varying with concentration proportionally to n^3. The duration of the pulsed chemical reaction stimulated by light is of the order of 10^{-8} sec, and varies proportionally to n^{-3}.

It is of interest to compare W with the reaction rate W_{sp} occurring under spontaneous luminescence into all modes:

$$W/W_{\text{sp}} \sim \pi^2 c^3 n / 4\omega_m^2 \Delta\omega = n / 4 \cdot 10^{12} \text{ cm}^{-3}. \tag{2}$$

For the concentrations under consideration, this ratio is much greater than 1. Consequently, spontaneous phototransitions cannot compete with stimulated ones.

The type of chemical laser considered above can also operate in a continuous regime if the gas mixture is blown through an optical resonator with mirrors.

Using a resonator with selective quality factor (for example, mirrors that reflect light only in a narrow frequency interval), one can impose on the laser the desired operating frequency ω. The latter can be chosen so that $\hbar\omega > \mathcal{E}$, the energy of the exothermic reaction. Let, for example, the reaction formula have the form $A_2 + B_2 = 2AB + \mathcal{E}$.

In Fig. 1, R symbolically depicts, in a planar scheme, the set of coordinates of the nuclei of a pair of molecules; $U(R)$ is the potential energy of the nuclei; E is the total energy of the system. Immediately after the phototransition of the electrons, the four-atom system A_2B_2 is formed, which then dissociates into $2AB$. For dissociation, the heat $\hbar\omega - \mathcal{E} > 0$ is required; it will be taken from the surrounding gas, which will rapidly cool it during the reaction, until the temperature drops so much that dissociation almost ceases. The temperature will then remain constant. In this way one can avoid the release of heat that destroys the laser and lowers its efficiency.

If $E_{A_2B_2}$ is the lowest vibrational level of the system, then cooling will continue even after the above-mentioned dissociation ceases, since in the emerging molecules A_2B_2 the vibra-

vibrational degrees of freedom will have a temperature equal to absolute zero.

If absorption of light in the mirrors, combinational scattering of light at the working frequency ω, etc., are neglected, then the light-stimulated chemical reaction can be carried out by a thermodynamically reversible route. The light energy obtained can exceed the energy released upon combustion of the same fuel by a factor of $\hbar\omega/\mathcal{E}$, at the expense of heat taken from the surrounding medium.

The photostimulation considered may also be of interest for chemical technology as a method for accelerating reactions and as a method for carrying out reactions that do not proceed by other means.

The reaction can be carried out in a multimode regime and without mirrors if the linear dimensions of the gas volume are considerably larger than $1/\alpha$.

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1. V. A. Fabrikant, M. M. Vudynskii, F. A. Butaeva, Author' s Certificate No. 148441 (576749/26 of 18 VI 1951); *Byull. izobr.*, No. 13 (1962).

2. N. G. Basov, A. M. Prokhorov, *ZhETF*, **27**, 431 (1954); A. M. Prokhorov, *ZhETF*, **34**, 1658 (1958); N. G. Basov, O. N. Krokhin, Yu. M. Popov, *UFN*, **72**, 161 (1960).

3. J. P. Gordon, H. J. Zeiger, C. H. Townes, *Phys. Rev.*, **95**, 282 (1954); A. L. Schawlow, C. H. Townes, *Phys. Rev.*, **112**, 1940 (1958); T. H. Maiman, *Nature*, **187**, 493 (1960); A. Javan, W. R. Bennet, D. R. Herriott, *Phys. Rev. Lett.*, **6**, 106 (1961).

4. J. C. Polanyi, *J. Chem. Phys.*, **34**, 347 (1961).

5. A. N. Oraevskii, *ZhETF*, **45**, 1771 (1963); *ZhETF*, **55**, 1421 (1968).

6. R. A. Young, *J. Chem. Phys.*, **40**, 1848 (1964).

7. V. L. Tal' roze, *Kinetika i kataliz*, **5**, 11 (1964).

8. *Appl. Optics Suppl. on Chem. Lasers*, 1965.

9. I. V. V. Kasper, G. C. Pimentel, *Phys. Rev. Lett.*, **14**, 352 (1965).

10. K. G. Anlauf, D. H. Maylotte et al., *Phys. Lett.*, **24A**, 203 (1967).

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