EFFICIENCY OF A PLASMA DYNAMIC LASER

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A fundamental aspect of the problem of developing short-wavelength lasers is the question of their efficiency [1]. Promising short-wavelength lasers are the plasma-dynamic lasers (PDL), referring to plasma-recombination lasers or lasers based on a recombining plasma (the word plasma refers, in accordance with the adopted terminology [2], to the aggregate state of the working body of the laser while recombination refers to the mechanism by which the upper working level is pumped). Based on the method employed to form the active medium – cooling by means of adiabatic expansion [3] – PDL are analogous to gas-dynamic lasers (GDL), and in addition this mechanism of cooling is most widely used. This circumstance limits the range of possible situations, so that cases when the plasma expansion is merely an unavoidable cofactor, while the main cooling mechanism is escape of radiation, or when expansion is necessary only for lowering the plasma density are of no importance for plasma-dynamic lasers.

The published data on the efficiency of plasma lasers are highly inconsistent. Thus in [4] it is stated that the efficiency of plasma-recombination lasers can reach 10%, while in [5] it is pointed out that the efficiency of lasers based on multiply charged ions (at the nonstationary stage of levelwise relaxation) equals to 10^{-8}-10^{-6}%.

The main purpose of this work is to give a reasonable representation of the structure of the total efficiency of PDL, which would enable efficient evaluation of the efficiency and comparison with the total efficiency of other types of lasers. Based on this representation an upper estimate of the efficiency of PDL based on 3s – 2p transitions of lithium-like ions is given.

The scheme of the process converting the energy E_0 injected into the PDL into the energy of the laser radiation E_t with the concomitant losses is shown in Fig. 1. The numbers 1-3 denote, respectively, the stages of excitation of the working body, the destruction of the equilibrium, and recombination, E_i is the initial energy of the working body, and, E_* is the excitation energy. According to this scheme the total efficiency of the PDL η, measured from the energy E_0 neglecting its quality, can be represented as a product of a series of factors, characterizing the efficiency of different stages of energy conversion:

$$\eta = \eta_s \eta_{tr} \eta_* \eta_n \eta_p \eta_r \eta_{ul} \eta_{st} \eta_c \eta_q. \quad (1)$$

Here η_s is the efficiency of the auxiliary system (analogous to [6]) and in Fig. 1 the energy losses in the auxiliary system are denoted by E_s, η_{tr} is the efficiency of energy transfer to the working body, i.e., the efficiency of the plasma source (in gas-discharge lasers this parameter corresponds to the efficiency of the discharge scheme [6], while in GDL it corresponds to the efficiency of the heaters [7]) and in Fig. 1 the energy losses in the plasma source are denoted by ΔE_{tr}; η_* is the ionization efficiency – the relative fraction of the energy of ionization of the recombining ions in the total enthalpy of the plasma (in electric discharge CO_2 lasers this is the vibrational efficiency of the pumping method [6], while in gas lasers it is the efficiency of thermal excitation [7]), and the losses accompanying the ionization of the working ions (thermal energy, energy of preliminary stages of ionization, etc.) in Fig. 1 are denoted by ΔE_*; η_n is the relative fraction of the energy of ionization of working ions which is conserved when the plasma expands to the region of the resonator (in the presence of a nozzle it is the efficiency of the nozzle by analogy to GDL [7]), and in Fig. 1, ΔE_r are the losses of ionization energy in the process of plasma expansion; η_p is the pumping efficiency – the relative fraction of the recombination flux populating the upper working level u, and in Fig. 1 the energy E_p corresponds to this flux and the energy ΔE_p corresponds to the losses; η_r is the recombination efficiency – the relative change in the degree of ionization of the working body in the region of the resonator; η_{ul} is the quantum efficiency – the ratio of the energy of the working transition to the ionization energy of the ionization stage corresponding to this transition, and the losses associated with η_{ul} are denoted in Fig. 1 by ΔE_{ul}; η_{st} is the relative probability of stim-

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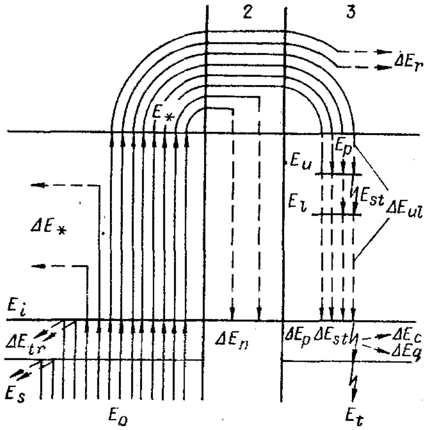

Fig. 1

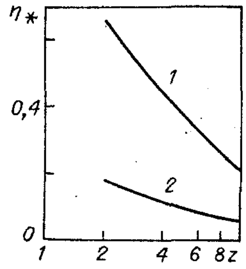

Fig. 2

ulated transitions in the overall decay of the upper working level (in [8] this parameter corresponds to the losses associated with deactivation by collisions), and in Fig. 1 E_{st} is the energy of the stimulated transitions and ΔE_{st} are the losses owing to spontaneous and collisional decay of the upper working level; η_c is the efficiency of the resonator, i.e., the efficiency of conversion of the energy of the working body by the resonator into the energy of the laser radiation; η_q is a coefficient that takes into account the optical nonuniformity of the working medium, associated with the presence of shock waves, turbulent pulsations, scattering, etc., and in Fig. 1, ΔE_c and ΔE_q are the losses corresponding to η_c and η_q.

The desirability of this detailed decomposition of the total efficiency into components lies in the fact that it reveals the least efficient stages of the energy conversion processes and the reasons for their low efficiency.

We shall analyze the efficiency of PDL without regeneration of energy losses on lithium-like ions, the possibility and the prospects of using which as working bodies in PDL were discussed in a number of works [1, 9-13]. The components of the total efficiency η_*, η_r, η_p, η_{ul} are evaluated most accurately.

Neglecting in a plasma of multiply charged ions the thermal energy compared with the ionization energy and assuming that the ionic composition of the plasma includes only the recombining and working ions (ions on whose transitions lasing is realized) with ionization multiplicity z and z − 1, respectively, the efficiency of excitation can be estimated as

$$\eta_* \cong 1 \Big/ \left(1 + (1/\alpha_z) \sum_{k=1}^{z-1} I_k/I_z\right), \tag{2}$$

where $\alpha_z = n_i^z/n$; n_i^z is the density of recombining ions; n is the density of atoms and ions of the working body; and I_z is the potential of the z-th stage of ionization. The values of η_* for $\alpha_z = 1$ and 0.1 (the lines 1 and 2) and z = 2-10 for a z-fold ionized plasma of lithium-like ions are presented in Fig. 2.

We shall estimate the relative change in the degree of ionization η_r in the region of the resonator (or, if there is no resonator, in the region where the threshold lasing condition holds, starting from the following considerations.

In the two-temperature model of the plasma in the absence of friction, heat conduction, and external fields the equations for the energy of the electrons and heavy particles have the form

$$\begin{gathered}\frac{3}{2}\frac{1}{T_e}\frac{dT_e}{dt} = \frac{1}{n_e}\left(\frac{dn_e}{dt}\right)^f + \frac{Q^r}{n_e k T_e} - \frac{Q^{\Delta T}}{n_e k T_e},\\ \frac{3}{2}\frac{1}{T}\frac{dT}{dt} = \frac{1}{n}\frac{dn}{dt} + \frac{Q^{\Delta T}}{nkT}.\end{gathered} \tag{3}$$

Here Q^r and $Q^{\Delta T}$ are change in the energy of the free electrons per unit time per unit volume during the recombination process and in elastic interactions with heavy particles; $(dn_e/dt)^f$ is the change in the electron density owing to expansion only (with absolutely frozen kinetics). To within the energy of the laser radiation we can set $Q^r \cong I_z(dn_i^z/dt)^r$ [$(dn_i^z/dt)^r$ is the rate of change of the density of working ions owing to recombination].

Compensation of the recombination heating of electrons in the region of the resonator (so that the condition $dT_e/dt \leq 0$ would hold) requires a certain rate of expansion of the plasma, whose lower limit can be estimated assuming that the plasma is isothermal $[(T_e - T)/T_e \ll 1]$. Then, setting in (3) $(1/T)dT/dt = (1/T_e) dT_e/dt \leq 0$, we obtain the condition for the electron temperature to be nonincreasing in the form

$$\frac{\tau_{\exp}}{\tau_r} \leqslant \frac{n_e + n}{n_i^z} \frac{kT_e}{I_z} = \frac{z + \alpha_z + 1}{\alpha_z} \frac{kT_e}{I_z}, \tag{4}$$

where $\tau_{\exp}$ is the characteristic time for the expansion of the plasma, equal to $[(1/V)dV/dt]^{-1}$ (V is the volume); $\tau_r = [(1/n_i^z)dn_i^z/dt]^{-1}$ is the characteristic time for recombination of ions of ionization multiplicity z, and, n_e is the electron density. The factor $\alpha_z/(z + \alpha_z + 1)$ is the ratio of the number of recombining particles to the number of particles absorbing recombination energy. In a plasma consisting of multiply charged ions, the latter are primarily electrons [their relative fraction equals $(z + \alpha_z)/(z + \alpha_z + 1)$], so that in such a plasma the cooling of electrons in elastic interactions with heavy particles cannot be the determining mechanism responsible for their cooling in a time segment of the order of the recombination time, as, for example, in a singly ionized plasma [14]. For this reason, the breakdown of thermal equilibrium accompanying the expansion of a plasma of multiply charged ions does not significantly affect the electron temperature.

For stationary expansion of the plasma in a wedge-shaped nozzle with an aperture angle $\theta \approx 90°$ in the region of the resonator $\tau_{\exp} \approx 10r/v$ (v is the velocity of the plasma at the stage of inertial expansion), so that the condition (4) determines the maximum characteristic size of the critical section r, enabling the achievement of the required plasma parameters.

For example, the region of existence of population inversion on the transition 3s−2p of lithium-like ions right up to F VII is bounded by the parameters [15] $T_e < 0.2z^{3/2}$ eV, $n_e > 3 \cdot 10^{12} z^7$ cm^{-3}. From here, the characteristic recombination does not exceed $\tau_r = 0.1z^{-11}$ sec. The recombination length $L = v/\tau_r$. To evaluate $v = [(\gamma(\gamma + 1)/(\gamma - 1))kT_*/m_\alpha]^{1/2}$, we can set $\gamma \approx 5/3$, $m_\alpha \approx 2M(z + 2)$, $T_* = T_{e*} \approx 3T_{ec}$ (M is the atomic unit of mass and T_{ec} is the temperature of the electrons in the region of the resonator), and then $v = 10^4[z^{3/2}/(z + 2)]^{1/2}$, i.e., v varies insignificantly in the region z = 2-10 and equals $(0.8\text{-}1.5) \cdot 10^6$ cm/sec. Setting $I_z \approx Ryz^2/4$, we obtain the limit for the maximum characteristic size of the critical section in a plasma of lithium-like ions $r < 10^4 z^{-10}/\alpha_z$ mm.

Some plasma parameters corresponding to this condition are given in Table 1. From the values of r and L presented there it follows that for $\alpha_z \approx 1$ B III is obviously the maximally ionized lithium-like ion which can be employed as the working body of a PDL on the transition 3s−2p. The minimum lasing wavelength λ in this case equals ~76 nm. The difficulty of achieving a population inversion on the transition 3s−2p in a plasma of lithium-like ions C IV, expanding in a stationary manner, is pointed out in [12].

It follows from the condition of efficient gas-dynamic cooling of the plasma (4) that the rate of change of the recombining-ion density accompanying expansion must be $[\alpha_z/(z + \alpha_z + 1)]I_z/kT_e$ times greater than the recombination rate, so that the efficiency with which the energy of the ionized continuum is utilized in the lasing zone – the recombination efficiency of the PDL η_r – cannot exceed the value $1/[1 + \alpha_z I_z/(z + \alpha_z + 1)kT_e]$, and it is all the higher the lower the value of α_z, but at the same time the efficiency of excitation η_* – the relative fraction of the ionization energy of recombining ions in the total enthalpy of the plasma (see Fig. 2) – decreases.

The condition (4) has essentially a dual meaning. From the viewpoint of the efficiency of neutralization of the recombination heating of the plasma it gives the upper limit for the value of r of a wedge-like nozzle, while from the viewpoint of the efficiency of the utilization of the energy of the ionization continuum this limiting value of r is optimal. In this case the lowest value of r will correspond to even larger losses of ionization energy accompanying expansion in a nozzle with this geometry ($\theta \approx 90°$).

Figure 3 shows the limiting values of the recombination efficiency η_r for $\alpha_z = 0.1$ and 1 (lines 1 and 2) and z = 2-10. Since the functions $\eta_* = \eta_*(\alpha_z, z)$ and $\eta_r = \eta_r(\alpha_z, z)$ vary as a function of both arguments in a directly opposite manner, it is desirable to study their product. The maximum values of the product $\eta_*\eta_r$ for the transition 3s−2p in a z-fold ionized lithium plasma are shown in Fig. 4 (curve 1). The quantum efficiency η_{ul} of lasers on the 3s−2p transitions of the isoelectronic lithium series varies from 0.28 for Li I up to 0.5 for F VII (the data on the excitation and ionization energies are taken from the tables in [16]). Figure 4 also shows the maximum values of the product $\eta_*\eta_r\eta_{ul}$ (curve 2). One can see that the value of this product does not depend strongly on z and equals 2-3%. For comparison we note that the analogous components of the efficiency equal 4-5% in gas-dynamic CO_2 lasers and 25-30% in gas-discharge lasers. Thus in spite of the

TABLE 1

Atom or ion	r, mm	L, mm	λ, nm
Li I	$10^4/\alpha_z$	10^6	813
Be II	$10/\alpha_z$	10^3	178
B III	$10^{-1}/\alpha_z$	10	76
C IV	$10^{-2}/\alpha_z$	10^0	42
N V	$10^{-3}/\alpha_z$	10^{-1}	27

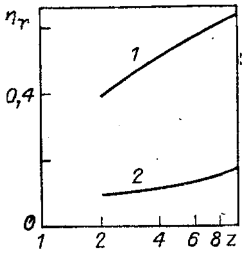

Fig. 3

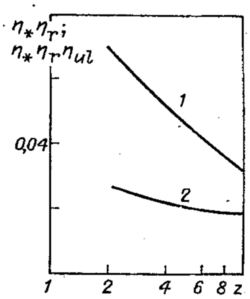

Fig. 4

much higher efficiency of excitation η_* in PDL compared with GDL ($\eta_T \approx 0.1$ [7]), the product $\eta_* \eta_r \eta_{ul}$ (in CO_2-GDL the parameter η_r corresponds to the efficiency of utilization of the vibrational energy of nitrogen) is practically identical in both cases, which is explained by the inadmissability of overheating of the working body in the region of the resonator in both cases.

The pumping efficiency for the 3s level was estimated from an analysis of the results of numerical calculations of the population kinetics of the levels of Li I in a recombining plasma. In the model of levelwise relaxation [12] employed in the calculations energy states with principal quantum number $n \geq 5$ were not studied, and the 3p, 3d and 4s, 4p, 4d, 4f states were combined into Boltzmann blocks with a distribution temperature equal to the electronic temperature, the recombination flux of electrons in the 4spdf block was determined in the diffusion approximation [17], and the lines in the main series were assumed to be fully reabsorbed. In the region $T_e = (2\text{-}3) \cdot 10^3$°K, $\eta_p \sim 0.5$-0.6, i.e., almost one-half of the recombination flux bypasses the upper working level.

Thus, based on the estimates obtained, the total efficiency of the PDL on lithium-like ions is bounded by the value

$$\eta = 0.01\eta_s\eta_{tr}\eta_n\eta_{st}\eta_c\eta_q. \tag{5}$$

Estimation of the components of the total efficiency, appearing in (5), with reasonable accuracy (of the order of 10%, if one takes into account the fact that there are six components) is a difficult problem, so that we shall confine ourselves to the following remarks. The upper estimate of the efficiency of stimulated transitions in the overall decay of the upper working level η_{st} is $1 - (n_u/g_u)(n_l/g_l)$, where n and g are the population and statistical weight of the upper u and lower l levels. The results of the numerical calculations show that, for example, for the 3s−2p transition in Li I $\eta_{st} \lessdot 0.3$. The efficiency of the nozzle, by analogy to nozzles in GDL, can be estimated as 0.5-0.7.

There is no unique definition of the efficiency of the resonator η_c in the literature. For example, in [2] the efficiency of GDL lasers is defined as the relative fraction of vibrational quanta entering together with the gas flow into the inlet of the resonator and converted into laser radiation quanta. Thus the efficiency of the resonator depends not only on the parameters of the resonator itself, but also on the character of the kinetic processes and the optical properties of the working body in the region of the resonator and equals in our case the complex $\eta_r\eta_p\eta_{st}\eta_c\eta_q$. In [7] this definition is narrowed and the resonator efficiency is defined as the ratio of the energy of the laser radiation to the total stored energy capable of being converted into radiation. In our case, as follows from (1), the resonator efficiency depends only on the parameters of the resonator itself, i.e., it takes into account the imperfection of its design [the nonoptimality of the type of resonator, its geometry and dimensions, losses to absorption and scattering in the mirrors (but not in the working medium), etc.] and is defined as the ratio of the laser radiation energy to the energy of the radiation from a laser with an ideal resonator, having zero losses and optimal mirror transmission coefficients, geometry, dimensions, etc.

As a function only of the losses β and the gain $\varkappa$ the expression for η_c has the form [7, 8] $\eta_c = [1 - (\beta/\varkappa)^{1/2}]^2$, whence it follows that it is possible to obtain for a gain exceeding losses by more than a factor of 10 a resonator efficiency of the order of 50%.

As a rule, there are no published explicit data on the value of η_s. In powerful commercial CO_2-lasers, however, η_s, defined according to the value of the total efficiency and the rest of its components, is of the order of 0.1 [6].

Thus, based on the expression (5) and the foregoing remarks, it may be assumed that the upper limit of the total efficiency of a PDL without regeneration of energy losses on the 3s−2p transition of lithium-like ions equals 10^{-3}, which is approximately an order of magnitude lower than the efficiency of CO_2-GDL (~1% [6, 7]). This is explained primarily by the comparatively low pumping efficiency η_p, owing to the branching of the recombination flux, and the low population inversion on the 3s−2p transition, owing to the low fraction of stimulated transitions in the decay of the upper level. The foregoing analysis also shows that for the restrictions employed for the region of existence of inversion on the 3s−2p transition of lithium-like ions, the ion B III is the ion with maximum ionization based on which a plasma-dynamic laser can be built.

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