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Kinetics of the active medium of a $He-Sr^+$ recombination laser: 2. Achievable energy characteristics

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***Abstract*. The mechanisms limiting the improvement of the energy characteristics of $He-Sr^+$ recombination lasers with increasing pressure, active volume, and pulse repetition rate are analysed. It is found that the existence of optimal pressure is related to the cooling rate limitation for electrons at high pressures arising from the heating action of the trailing edge of a current pulse and that the average power saturation with increasing discharge tube diameter and pulse repetition rate occurs due to the formation of radial nonuniformity as well as due to the growth of the electron temperature in the afterglow. Calculations involving a mathematical model showed that the attainable maximum of the linear power is equal to $\sim$6.2 W m^{-1} for self-heating active elements of BeO ceramics and to $\sim$7.8 W m^{-1} with its surface blackened, to $\sim$7.7 W m^{-1} for an independent introduction of the vapour and to $\sim$9.4 W m^{-1} in combination with blackening, to $\sim$17 W m^{-1} for intense forced cooling of the active elements of cylindrical geometry and to $\sim$29 W m^{-1} with active elements of rectangular cross section for a wall dimension ratio of 1 : 3. We demonstrate the feasibility of raising the output power by $\sim$21 % in the excitation of the active medium by pulse bursts with a short interpulse separation.**

Keywords: *$He-Sr^+$ recombination laser, self-heating regime, energy characteristics, mathematical simulation.*

1. Introduction

Ion recombination strontium vapour lasers are efficient sources of short-wavelength radiation at wavelengths of 430.5 and 416.2 nm with typical levels of average output power of 1.0 – 1.5 W, a peak power of 1 – 1.5 kW, and a laser pulse duration of 200 – 300 ns (for pulse repetition rates of 5 – 10 kHz, an efficiency of $\sim$0.1 %, and the gain of the active medium of $\sim$0.05 – 0.1 cm^{-1} [1 – 4]. These lasers are pumped by collisional-radiative recombination of doubly charge strontium ions in the afterglow of a pulsed discharge, the population inversion being achieved as a result of efficient depopulation of the lower laser levels due to electron deexcitation.

The highest output parameters of $He-Sr^+$ lasers excited by a longitudinal discharge that have been experimentally achieved to date are as follows: an average output power of 3.9 W [5, 6], a linear average output power of 11.8 W m^{-1} [5, 6], a specific average output power of 277 mW cm^{-3} [7], a pulse energy of 6 mJ [8], a peak power of 20 kW [8], and a gain of 0.15 cm^{-1} [7].

The data of numerous investigations suggest that the energy characteristics may be augmented by increasing the pressure of the active medium, the transverse dimensions of the active element, and the pulse repetition rate only when these parameters are within certain ranges [1 – 14]. The aim of our work is to analyse the physical mechanisms which limit the growth of the energy characteristics of $He-Sr^+$ lasers as well as to search for the possible ways of improving the lasing characteristics and calculate the attainable energy characteristics.

2. Improvement of energy characteristics with increasing active medium pressure

In experiments aimed at the optimisation of self-heating $He-Sr^{-1}$ lasers, the growth of average output power with increasing helium buffer gas pressure p_{He} is observed up to the optimal pressure $p_{He\,opt} \sim 0.4 - 0.9$ atm [1 – 4, 10, 11, 13]. Figure 1 shows the experimental dependences of the average output power P_{av} and efficiency as well as of the pulse-repetition rate f on the helium pressure, which we obtained for different storage capacitances C and a self-heating laser tube with an active length $l = 45$ cm and an internal diameter $d = 1.5$ cm. Figure 2 shows the experimental oscilloscope traces of the current and lasing pulses for different helium pressures.

The growth of average output power with increasing pressure up to its optimal values (Fig. 1a) is due to the growth of the laser pulse energy (Fig. 2), which is caused by the enhanced cooling of electrons in elastic collisions with helium atoms and ions. The rapid electron cooling permits increasing the strontium vapour pressure and the density of recombining Sr^{++} ions with maintenance of a low level of the electron temperature T_e in the early afterglow and hence affording the increase in the recombination pumping rate for SrII levels with increasing p_{He}.

With increasing pressure the pulsed energy input into the discharge also increases, which is required to ensure the double ionisation of the rising number of strontium atoms. The frequency f lowers in this case (Fig. 1b), resulting in the

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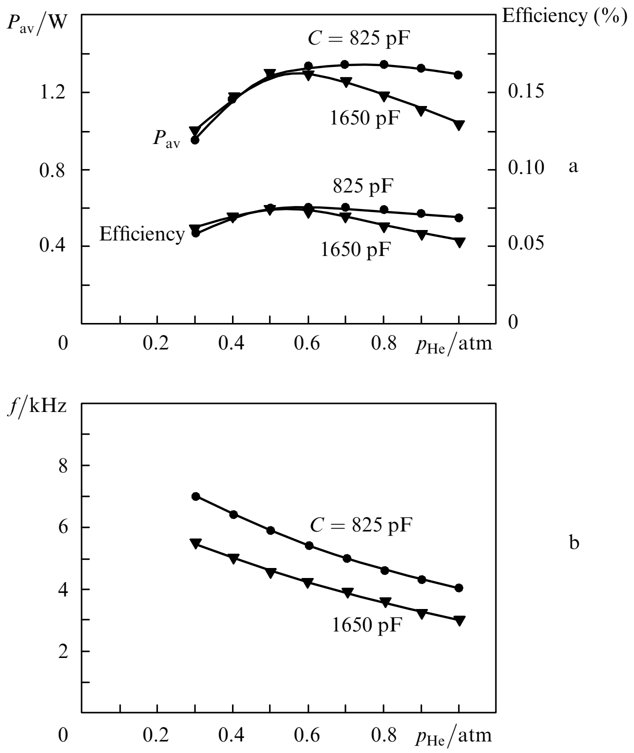

Figure 1. Average output power, efficiency (a), and pulse repetition rate (b) as functions of helium pressure determined experimentally for a self-heating $He-Sr^+$ laser for different values of the storage capacitance C ($l = 45$ cm, $d = 1.5$ cm).

maintenance of the thermal balance of the laser tube in the self-heating regime.

As pHe exceeds the optimal value, the average output power becomes lower (Fig. 1a). The oscilloscope traces of current and laser pulses (Fig. 2) demonstrate the following fact: with increasing pressure, the recombination pumping is earlier 'engaged' and laser pulse 'presses itself' to the trailing edge of the current pulse, because the electrons cool down faster in the afterglow. An analysis of experimental data revealed that the existence of optimal helium pressure is associated with the limitation of electron cooling rate in the early afterglow arising from the heating action of the trailing edge of the current pulse. This action manifests itself when the electron cooling time τ_{cool}, which shortens with increase in p_{He}, becomes comparable with the trailing-edge (fall) time τ_f of the current pulse. The fall time is defined by the storage capacitance and the tube inductance and is hardly dependent on the pressure [the magnitude of τ_{cool} can be judged by the delay between the current and lasing pulses (Fig. 2) for $p_{He} \leqslant p_{He\,opt} = 0.7$ atm].

Therefore, while for $p_{He} < p_{He\,opt}$ the phase of recombination 'engagement' is determined by the T_e fall time due to elastic electron collisions with helium atoms and ions and shortens with increasing p_{He}, for $p_{He} > p_{He\,opt}$, when the trailing edge of the current pulse begins to exert effect and heat the electron gas, this phase is now defined by the trailing-edge time and is hardly dependent on p_{He}. As a result, at pressures exceeding the optimal one, there grows the fraction of Sr^{++} ions uselessly recombining at the beginning of recombination pumping. These 'useless ion losses' occur both prior to the onset of lasing threshold and early in the pulsed lasing, when the optimal conditions for recombination pumping have not been reached. As a consequence, the growth of the pumping rate and hence the growth of pulse energy characteristics with increasing p_{He} slows down (see Fig. 2), and the efficiency becomes lower (Fig. 1a).

In the self-heating regime the average output power P_{av} is determined by the efficiency η and the source power consumption P_{in}, which is equal to the thermal power Q scattered by the laser tube due to convection and the thermal radiation for the optimal wall temperature: $P_{av} = \eta P_{in} = \eta Q$. In this case, because of steep temperature dependence of the saturated strontium vapour pressure, the growth of strontium vapour pressure, which is required in the case of increasing p_{He}, is provided by only a relatively small rise in the temperature of the active element and accordingly by a small rise in its power consumption. Due to a weak dependence of P_{in} on p_{He}, the dependences of η and P_{av} on the pressure are almost the same, and an appreciable lowering of the efficiency accordingly leads to a lowering of the average output power (Fig. 1a). So, although the laser pulse energy E rises with pressure also for $p_{He} > p_{He\,opt}$ (Fig. 2), the lowering of its growth rate because of the increase in the fraction of uselessly recombining Sr^{++} ions at the initial stage of pumping leads, for a decreasing frequency f (Fig. 1b), to a lowering of the average output power $P_{av} = Ef$ for $p_{He} > p_{He\,opt}$ (Fig. 1a).

The established mechanism of the growth limitation for recombination laser energy characteristics enables explaining the experimentally observed increase in the optimal pressure with a decrease in the storage capacitance (Fig. 1a) and proposing the ways of increasing $p_{He\,opt}$ and P_{av}. The optimal pressure corresponds to the conditions whereby the electron cooling time $\tau_{cool} \propto 1/p_{He}$ is approximately equal to the trailing-edge (fall) time of the current pulse $\tau_f \propto (LC)^{0.5}$ (L is the tube inductance) [12], and therefore $p_{He\,opt} \propto 1/(LC)^{0.5}$. Clearly by decreasing C it is possible to increase $p_{He\,opt}$ and accordingly the average output power. However, the possibility of changing C is limited by the necessity of fulfilling the condition of matching the active element with the electric pump circuit: $R = 2(L/C)^{1/2}$ (R is the plasma resistance) [12]. A mismatch, as is evident from Fig. 2, leads to undesirable current pulsations in the early afterglow, which is responsible for electron heating and the consequential dip in lasing pulses due to a steep dependence of the three-body electron–ion recombination coefficient α on the electron temperature ($\alpha \propto T_e^{-9/2}$) [1–4]. The matching requirement is especially strict at high pressures, when the delay between the current and lasing pulses is minimal.

An increase in $p_{He\,opt}$ and P_{av} may also be provided by lowering the tube inductance L. This can be attained, for instance, by using a coaxial laser tube design with a reverse current conductor [15].

Another, more radical way of improving the energy characteristics at high pressures consists in an abrupt termination of the current pulse in the trailing edge. Clearly $p_{He\,opt}$ will unrestrictedly increase as $\tau_f \to 0$ (in the absence of other limiting factors). A technical solution enabling an abrupt current termination with the help of an additional chopping thyratron was proposed in Ref. [16].

Figures 3 and 4a show the results of numerical calculations which illustrate the potentialities of self-heating $He-Sr^+$ lasers with increasing pressure. The calculations were

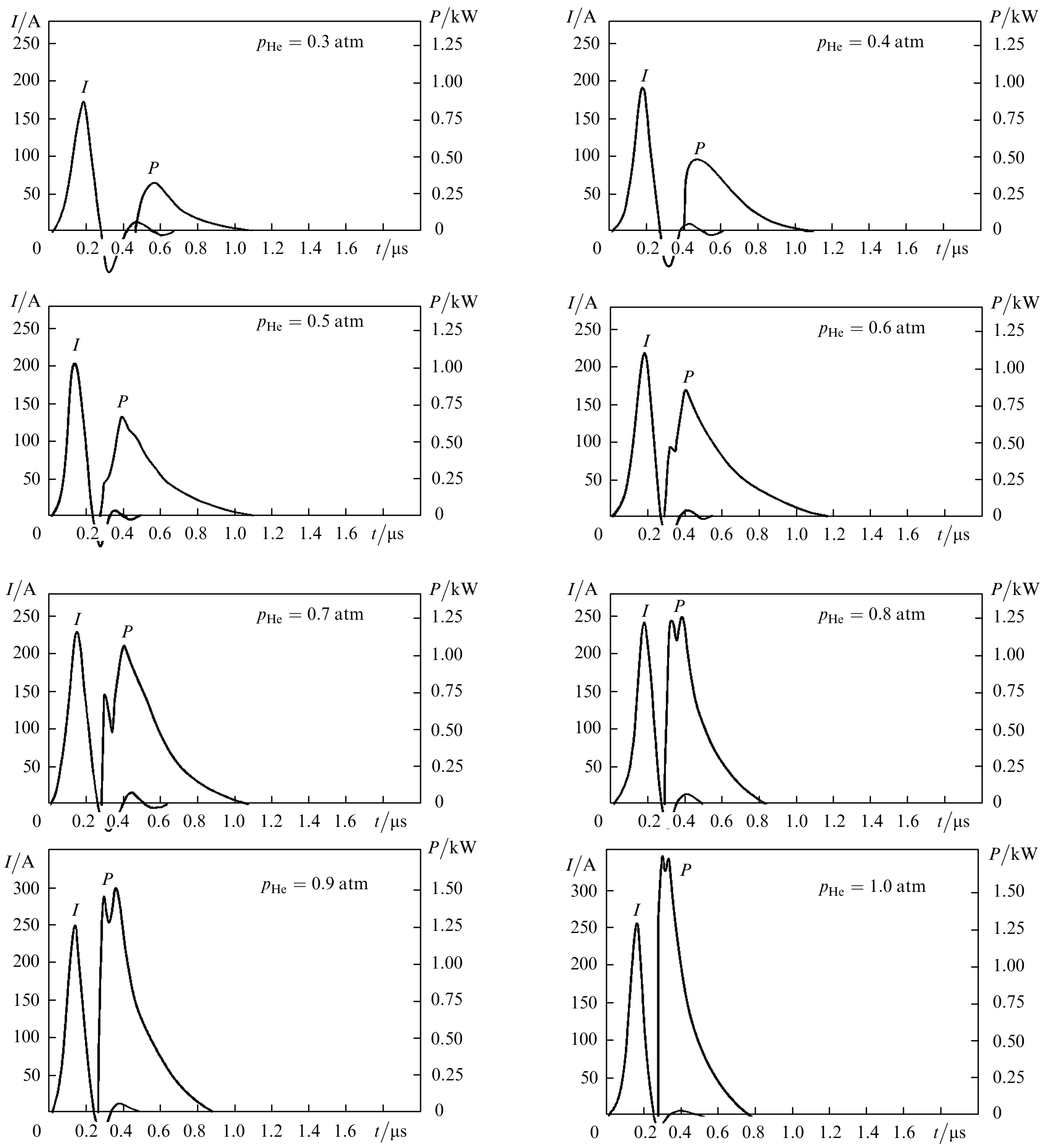

Figure 2. Experimental oscilloscope traces of the current and lasing pulses of a self-heating He – Sr$^+$ laser for different p_{He} values ($l = 45$ cm, $d = 1.5$ cm, $C = 825$ pF).

performed employing the mathematical model of Ref. [17]. The optimal excitation regimes were automatically found with the use of a numerical multiparametric optimisation.

One can see from Figs 3a – 3c that for an optimal pressure of 0.7 atm, when the electron cooling time is still relatively long, the current pulse termination has only an insignificant effect on the pumping and the lasing, while for an increased pressure of 1.5 atm (Figs 3d – 3f), when the heating action of the trailing edge of a current pulse begins to exert effect, its termination leads to an increase in recombination pumping W_r due to a lowering of the fraction of uselessly recombining Sr^{++} ions and hence to a growth of the peak output power and laser pulse energy.

The calculated data given in Fig. 4a illustrate the possibility of raising the optimal helium pressure and the average output power by lowering the storage capacitance. Employing the interruption of a current pulse permits overcoming the pressure constraint and obtaining a monotonic growth of the output power with increasing pressure.

If an independent introduction of the metal vapour into the active medium is provided (for instance, due to helium circulation [9, 14, 16] or cataphoresis [7, 18, 19]), the pulse repetition rate will evidently be an independent optimisation parameter and the value of f may be fixed. In this case, the dependence of the output laser power on the helium pressure will be determined by the p_{He}-dependence of the pulse energy E rather than of the efficiency. The former may rise with increasing p_{He} up to several atmospheres [9]. Figure 4b shows the results of our calculations and of the experiment of Ref. [9], which illustrate the potentiality of He – Sr$^+$

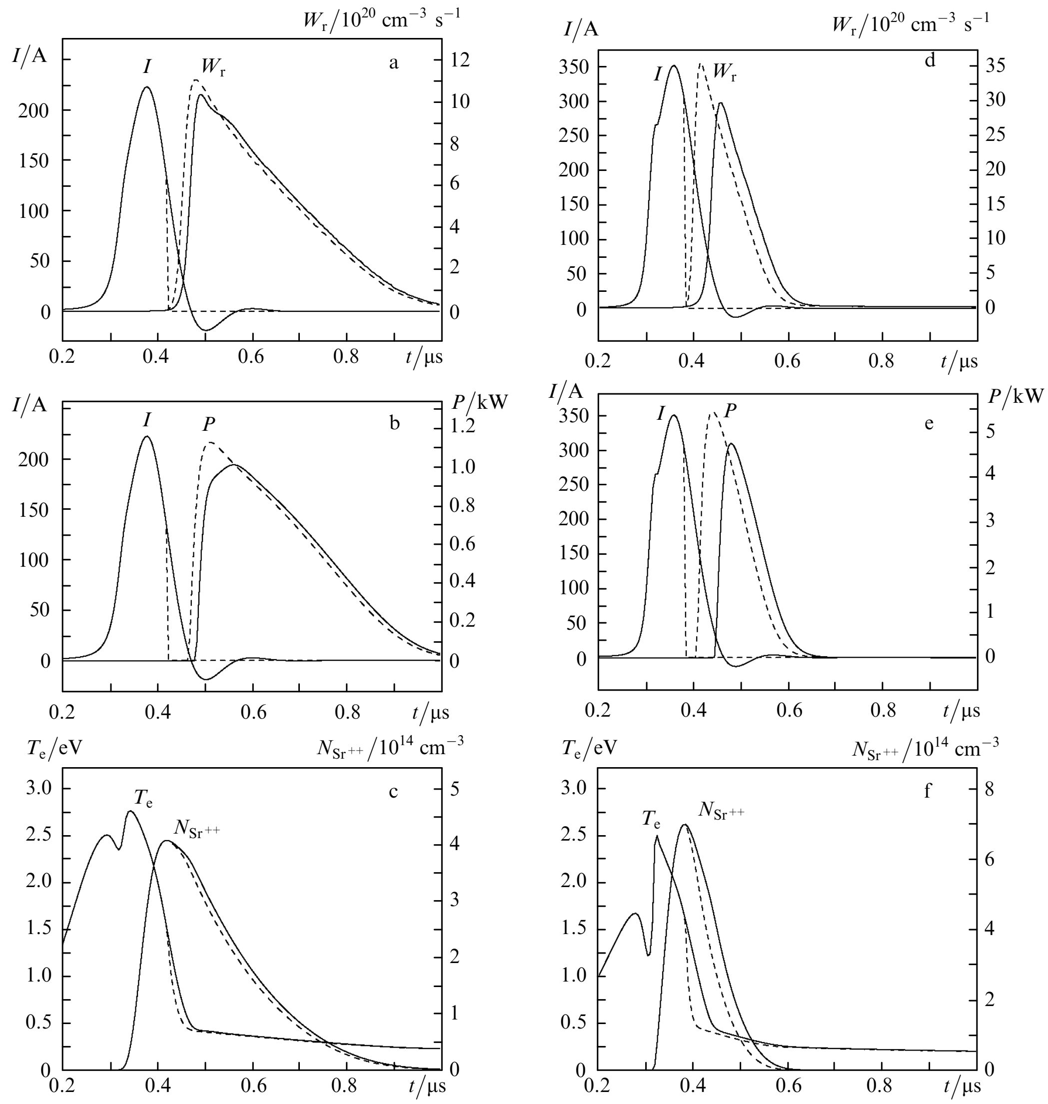

Figure 3. Calculated time dependence of the current pulses (a, b, d, e) and lasing pulses (b, e) for a self-heating $He-Sr^+$ laser, the recombination pumping rate W_r (a, d), the electron temperature and the doubly charged strontium ion density (c, f) for $p_{He} = 0.7$ (a–c) and 1.5 atm (d–f); solid curves – ordinary lasing regime, dashed curves – current pulse termination regime ($l = 45$ cm, $d = 1.5$ cm, $C = 825$ pF).

lasers with an independent introduction of the metal vapour (for a fixed value $f = 3.2$ kHz) at high p_{He}. Clearly the mechanisms considered above would give rise to an optimum in the p_{He}-dependences of E and P_{av} at pressures of the order of several atmospheres for an independent vapour introduction as well (Fig. 4b). The ways of improving the output characteristics of self-heating lasers proposed above, in particular a lowering of the storage capacitance and a sharp termination of the current pulse, are also applicable for an independent vapour introduction, as evidenced by Fig. 4b.

3. Improvement of energy characteristics with increasing volume of the active medium and pulse repetition rate

One way of improving the energy characteristics of $He-Sr^+$ lasers consists in an increase in the active medium volume by increasing the length and diameter of the active elements. Furthermore, in several cases this improvement may be achieved by raising the pulse repetition rate.

Our experiments showed that the average output power of $He-Sr^+$ lasers increases virtually in proportion with the active length, so that the linear power is almost independent of the length. The length of the active elements may be limited by the technical capability of increasing the voltage across the gas-discharge gap. This limitation may be removed by using sectioned active elements. In particular, an average 3-W output was achieved employing a two-sectional self-heating tube with a length $l = 90$ cm and a diameter $d = 1.5$ cm in Ref. [20].

However, the growth of linear output power with increase in diameter of self-heating active elements moderates and then saturates, as evidenced by the data of our experiments on tubes of different geometry (Fig. 5a). In this case, the optimal pulse repetition rate decreases with increasing diameter (Fig. 5b).

Let us analyse the reason of this behaviour of the linear output power. The energy E of laser pulses, the pulse repetition rate f, and the average output power P_{av} of self-heating $He-Sr^+$ lasers is scaled in accordance with the relations [12]

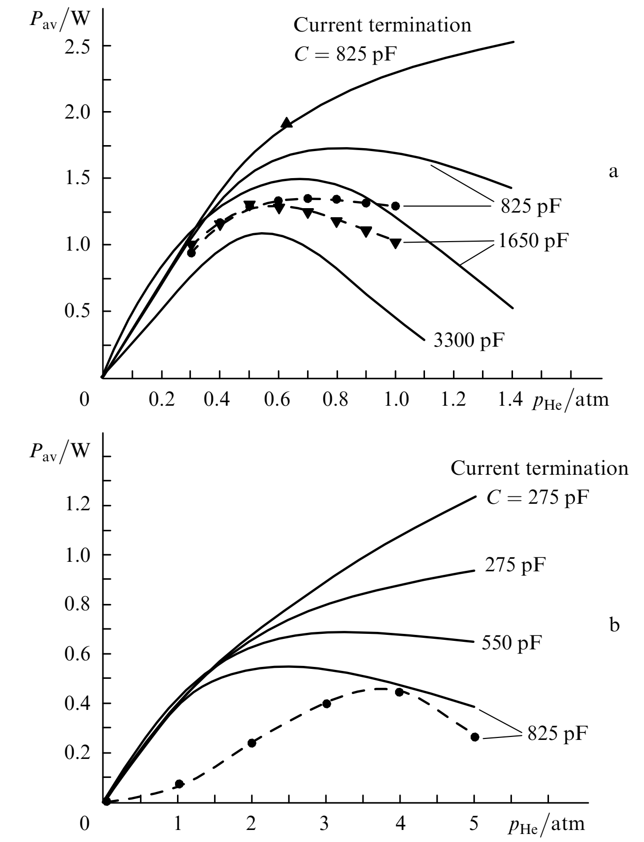

Figure 4. Calculated dependences of the average output power of He – Sr$^+$ lasers on the helium pressure; a – self-heating regime: $l = 45$ cm, $d = 1.5$ cm (●, ▼ – our experiment for a tube with $l = 45$ and $d = 1.5$ cm, ▲ – experiment of Ref. [16] for a tube with $l = 50$ and $d = 1.5$ cm); b – independent introduction of strontium vapour: $l = 22$ cm, $d = 0.8$ cm (● – experiment of Ref. [9] for a tube with $l = 22$ cm, $d = 0.8$ cm).

$$E = \eta w V \propto \eta w d^2 l, \tag{1}$$

$$f \propto \frac{d_{out}}{wd^2} \propto \frac{1}{wd}, \tag{2}$$

$$P_{av} = Ef \propto \eta l d_{out} \propto \eta l d, \tag{3}$$

where V is the active volume; d_{out} is the outer diameter of a laser tube; and w is the specific energy input, which is of the same order of magnitude for tubes of different geometry and which assumes values in the 2 – 10 mJ cm^{-3} range. Simplifications were made in expressions (2) and (3) assuming $d_{out} \propto d$, which is the case for typical tubes of BeO ceramics used in He – Sr$^+$ lasers. In accordance with expression (1), when there are no limiting factors and $\eta \approx 0.1\,\% \approx$ const, the specific energy output $E/V = \eta w$ is also of the same order of magnitude for tubes of different geometry and normally amounts to 2 – 10 μJ cm^{-3}. Note that the highest average output power in the self-heating regime is not necessarily achieved for the highest specific energy output, because it corresponds to the highest efficiency, and not to the highest pulse energy.

According to expression (2), the pulse repetition rate decreases with increasing the diameter. This is due to the necessity of maintaining a constant thermal regime of the self-heating active element and keeping the optimal temperature of the inner wall of the laser tube and, accordingly, the optimal metal vapour pressure. Indeed, for $w \approx$ const the power consumed by the active element is defined by the relation

$$P_{in} = wVf \propto ld^2 f \tag{4}$$

and is equal to the thermal power carried away from the ceramic laser tube by means of convective heat exchange and thermal radiation [21],

$$Q = l\big[0.0277(T + T_a)^{0.2}(T - T_a)^{1.25} d_{out}^{0.75}$$

$$+ 1.78 \times 10^{-9} d_{out} \varepsilon T^4\big] = l(A(T) d_{out}^{0.75} + B(T) d_{out}). \tag{5}$$

Here, ε is the emissivity of the tube surface (for BeO ceramics $\varepsilon \approx 0.5$); the length l is taken in metres, the diameter d_{out} – in centimetres, the tube wall temperature T and the ambient air temperature T_a – in Kelvins, and the thermal power Q is defined is Watts. In view of the fact that the radiative heat removal, which is described by the second term, prevails and assuming that in the self-heating regime for the optimal wall temperature the coefficients A and B are approximately constant, expression (5) may be simplified: $Q \propto l d_{out}$. In this case, from expressions (4) and (5) it follows that the invariance of the frequency f with increasing diameter may be afforded only for $d_{out} \propto d^2$, which does not correspond to the geometry of typical BeO tubes. That is why for $d_{out} \propto d$ we have $f \propto 1/d$. Therefore, in the absence of limiting factors (i.e., for $\eta \approx$ const), in accordance with expression (3) it is possible to obtain for the linear output power

$$\frac{P_{av}}{l} \propto d. \tag{6}$$

As is clear from our experimental data (Fig. 5a), the close-to-linear growth of the linear output power with diameter takes place until $d \sim 2$ cm. The power saturation observed for $d > 2$ cm is due to the action of limiting mechanisms responsible for a lowering of the efficiency and, in accord with expressions (1) and (3), for a moderation of the growth of energy characteristics. We consider these mechanisms.

Among the factors responsible for efficiency lowering is the formation of a radial nonuniformity of the active medium [6, 13, 19]. The axial overheat of the active medium will increase with increasing diameter due to impairment of the conditions for heat removal from the axial parts of the tube. Due to thermal diffusion this will lead to a deepening dip in the prepulse radial density distribution of metal atoms as well as of helium atoms. Furthermore, an additional contribution to the formation of the radially nonuniform density profile of metal atoms is made by radial cataphoresis [19]. The lowering of atomic Sr density in the axial tube region is responsible for a lowering of the pumping rate and efficiency of the He – Sr$^+$ laser, because the radial density distribution of recombining Sr^{++} ions virtually replicates, under the conditions whereby strontium is doubly ionised almost completely, the prepulse radial density distribution of atomic Sr (with the exception of the thin wall region).

In Ref. [19] we obtained a criterion for the spatial uniformity of the active medium, whence it follows that

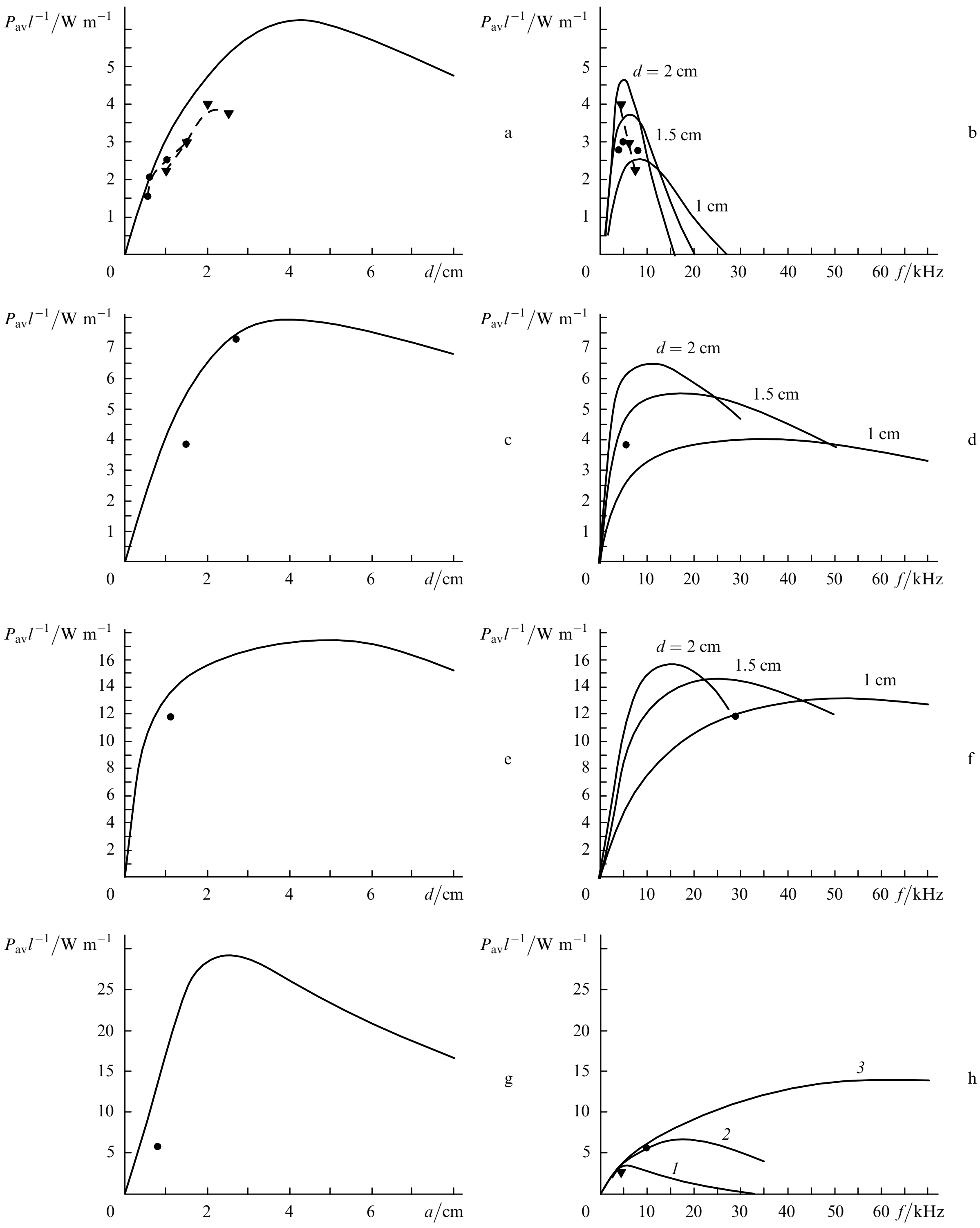

Figure 5. Calculated dependences of the average linear output power of He – Sr^+ laser radiation on the transverse dimension of the active medium and the pulse repetition rate; a, b – self-heating regime [● – our experiment for tubes with $l = 9$ cm and $d = 0.55$ cm, $l = 20$ cm and $d = 0.6$ cm, $l = 25$ cm and $d = 1.0$ cm, $l = 45$ cm and $d = 1.5$ cm (a) and for a tube with $l = 45$ cm and $d = 1.5$ cm (b); ▼ – our experiment for tubes with $l = 40$ cm and $d = 1.0$, 1.5, and 2.0 cm (a, b), as well as $d = 2.5$ cm (a)]; c, d – independent introduction of the metal vapour [● – experiment of Ref. [16] for tubes with $l = 28$ cm and $d = 2.7$ cm (c), $l = 50$ cm and $d = 1.5$ cm (c, d)]; e, f – forced tube cooling (● – experiment of Refs [5, 6] for a tube with $l = 33$ cm and $d = 1.1$ cm); g, h – rectangular tube cross section for $a:b = 1:3$ (g) and for $a = 0.8$ cm and $b = 2.4$ cm (h); (*1*) – self-heating regime, (*2*) – independent vapour introduction, (*3*) and g – forced tube cooling (● – experiment of Ref. [11] for a tube with $l = 40$ cm, $a = 0.8$ cm and $b = 2.4$ cm with a water cooling and ▼ – in the self-heating regime).

increasing the diameter d generates a need for more sharp, than by formula (2), lowering of the frequency to retain uniformity with increasing diameter:

$$f \propto \frac{1}{wd^2}. \tag{7}$$

The average linear power will saturate in this case:

$$\frac{P_{av}}{l} = \frac{\eta w V}{l} f \propto \frac{\eta w d^2 l}{l} \frac{1}{w d^2} \propto \eta \approx \text{const.} \quad (8)$$

However, for an invariable thermal regime of a self-heating tube, which is afforded at frequencies defined by expression (2), the degree of nonuniformity of the active medium will increase with diameter and the efficiency will become lower.

We emphasise that the growth of the gas temperature T_g in the axial tube regions as well as of the section-averaged gas temperature, which takes place with increase in the diameter, will be attended by the growth of T_g in the afterglow [6, 13]. This will lead to a lowering of the population inversion and the efficiency due to a decrease in the recombination pumping rate for the upper laser level and a moderation of the electron deexcitation of the lower laser level, as well as due to an increase in the rate of its electron collisional excitation from low metastable levels and the ground state of SrII. This, along with the formation of a spatially nonuniform active medium, is another substantial factor which limits the growth of energy characteristics with increasing d.

When the pulse repetition rate departs from the optimal value, the average output power in the self-heating regime becomes lower due to a departure of the energy input from the optimum required to maintain the thermal tube regime, as evidenced by experimental data (Fig. 5b). This lowers the efficiency. It is therefore evident that in the self-heating regime the frequency is not an independent parameter, and its increase does not lead to a growth of the output laser power.

We performed numerical calculations of the attainable linear output power of He – Sr^+ lasers taking into account the influence of the limiting factors mentioned above on the characteristics of lasing. When varying the diameter d we employed the values of outer diameter d_{out} and surface emissivity ($\varepsilon = 0.5$) typical for BeO tubes. The excitation conditions were automatically optimised. Varying the active length showed that the attainable linear output power hardly depends on it.

In the simulation of the self-heating regime, the frequency was determined from expression (4) and (5): $f = Q/(wV)$. These simulations yielded the diameter dependence of the linear output power for self-heating lasers, which is depicted in Fig. 5a. In these simulations, the frequency was also varied under the conditions of constant power consumed by the tube, which was maintained by varying the energy input (Fig. 5b). One can see from Fig. 5b that the range of possible variations of f in the self-heating regime is relatively narrow. In this case, the optimal f value lowers with increasing diameter. The calculated data are consistent with our experimental data. Referring to Fig. 5a, the power saturation occurs for $d \sim 4$ cm, and then it decreases. The maximal linear output power attainable in the self-heating regime is equal to ~ 6.2 W m^{-1}.

We analyse the possible ways of raising the output power of He – Sr^+ lasers. Blackening the tube surface permits increasing ε to 0.9 – 1.0 [1 – 4, 11, 21], which will lead to an increase in the power removed from the tube due to the thermal radiation because of the increase in the second term in expression (5) and, accordingly, to an increase in frequency and output laser power. In this case, in accord with expression (5) the power carried away and the frequency may rise by $\sim 67\,\%$ for an optimal temperature $T \sim 600\,^{\circ}$C. With increasing frequency, however, because of an axial temperature growth the increase in output power will be smaller and it will become smaller with increasing diameter. Calculations showed that the maximal linear output power attainable with blackening in the self-heating regime may range up to ~ 7.8 W m^{-1}.

Increasing the outer tube diameter by employing a thick-walled ceramics also increases heat removal and permits, in accordance with expression (2), raising the frequency and hence the output power [1 – 4]. Employing a thick-walled ceramics with $d_{out} \approx 3.7d$ in a self-heating cataphoresis He – Sr^+ laser enabled us to obtain a high frequency ($f \sim 30$ kHz) and a record-high specific average output power of 277 mW cm^{-3} [7, 11]. Clearly the heat removal may also be increased by other means of increasing the external surface, for instance, by endowing the tube with ribs [1, 2].

The removal of metal from the discharge zone and its stay in the slots of sectioned tubes, and also independent introduction of the metal vapour by helium circulation or cataphoresis make it possible to 'decouple' the wall temperature and the vapour pressure [1 – 4, 7, 14, 16]. In this case, the frequency is no longer limited by expression (2) and may be higher than in the self-heating regime. However, due to a limited rate of heat removal for a free cooling of the laser tube, a significant increase in frequency will lead to an increase in wall temperature, with the consequential rise of the gas temperature over the entire tube section, and the greater the tube diameter, the greater the temperature increase. This will lead to engagement of the afore-mentioned limiting factors.

Figure 5c and 5d show the calculated linear output power under the conditions whereby the atomic strontium density is independent of the wall temperature [determined by solving the equation $Q(T) = wVf$ при $\varepsilon = 0.5$], which corresponds to the regime of independent vapour introduction. In this regime the optimal frequencies and the output power are higher than in the self-heating regime. The results of simulations are in good agreement with the experimental data of Ref. [16] concerned with investigations of He – Sr^+ lasers with an independent vapour introduction due to forced helium circulation. The behaviour of the optimal frequency with diameter variation in Fig. 5d is consistent with the experimental dependence $f_{opt} \propto 1/d$ [14]. According to calculations, the output power saturation for an independent vapour introduction also sets in for $d \sim 4$ cm and the attainable maximum of the linear output power amounts to ~ 7.7 W m^{-1} (Fig. 5c). Calculations suggest that blackening the tube surface may increase this maximum to ~ 9.4 W m^{-1}.

Replacing the free convective cooling by intense forced cooling (air or water cooling) permits a substantial increase in frequency and output power with retention of the inner-wall tube temperature at the optimal level due to a sharp intensification of the heat removal [1 – 6, 11, 21, 22]. In this case, the way of introducing the vapour and the value of ε are no longer of major importance. The action of limiting factors will also lead to power saturation with increase in diameter and frequency. However, this saturation will take place at a substantially higher level, because the overheat of the active medium will be much weaker than for an independent vapour introduction and a free cooling of the laser tube.

Figures 5e and 5f show the calculated linear output power for the optimal and invariable temperature of the tube wall, which corresponds to the regime with intense forced cooling. In this regime, the optimal frequencies and the output power are even higher than in the regimes considered earlier. The results of simulations are in agreement with the experimental data of Refs [5, 6] with the use of water cooling, which enabled raising the frequency up to 29 kHz and attaining an average output power of 3.9 W, a record for $He-Sr^+$ lasers. The frequency dependence for $d = 1$ cm (Fig. 5f) agrees well with that obtained in Ref. [6], and the variations of the optimal frequency with diameter variations are consistent with the relation $f_{opt} = 55/d^2$ (f_{opt} is taken in kilohertz and d – in centimetres) [6]. According to calculations, the output power saturation for the forced cooling sets in for $d \sim 5$ cm and the attainable maximum of linear output power amounts to ~ 17 W m^{-1} (Fig. 5e).

The use of a laser tube of rectangular cross section [3, 11, 23, 24] permits a substantial increase in the active volume, for which the action of limiting mechanisms will become significant, in comparison with a tube of cylindrical geometry and thereby raise the attainable output power. This possibility is related to the fact that the axial gas temperature is determined by the minimal transverse tube dimension, i.e. by the narrow wall dimension a, which defines the conditions of thermal transfer from the axial regions of the tube. By selecting the optimal value of a, when the overheat of the axial tube region is not yet strong, it is possible to build up the cross-sectional area and the volume by increasing the wide wall dimension b.

We calculated the linear output power of $He-Sr^+$ lasers with tubes of rectangular cross section. To this end, in the kinetic equations of our model which take into account the transfer processes, the tube diameter was replaced by the effective transverse dimension. This dimension was equated to the narrow wall dimension a, while the plasma resistance and the active volume were found proceeding from the rectangular cross section of the tube.

The results of simulations for $a:b = 1:3$ are shown in Figs 5g and 5h. One can see that the simulation data agree well with the experiment of Refs [3, 11] with a tube of rectangular cross section (0.8×2.4 cm), which operated both in the self-heating regime and with the use of water cooling. According to these calculations, the attainable linear output power maximum with a forced cooling amounts to ~ 29 W m^{-1} and is reached for a $\sim 2.5\times$ 7.5-cm tube cross section (Fig. 5g). The calculations also showed that the linear output power rises monotonically with increasing the dimension b for a fixed dimension a. Therefore, the limitations in transverse dimensions of the active medium are removed for $He-Sr^+$ lasers with tubes of rectangular cross section. A faster, than for cylindrical tubes, fall of the linear output power for greater transverse dimensions (Fig. 5g) is caused by the following fact. Due to the lower plasma resistance, the matching of the active element with the pump circuit is reached for higher storage capacitances, resulting in longer trailing-edge times of the current pulse and the consequential lowering of the characteristics of lasing.

4. Improvement of energy characteristics in the regime of excitation by pulse bursts

The bulk of doubly charged strontium ions recombining in the early afterglow are produced by stepwise ionisation during the course of a current pulse. The recombination coefficient α depends rather sharply on the ion charge Z ($\alpha \propto Z^3 \ln (Z^2+1)^{1/2}$) [1–4], with the consequence that the

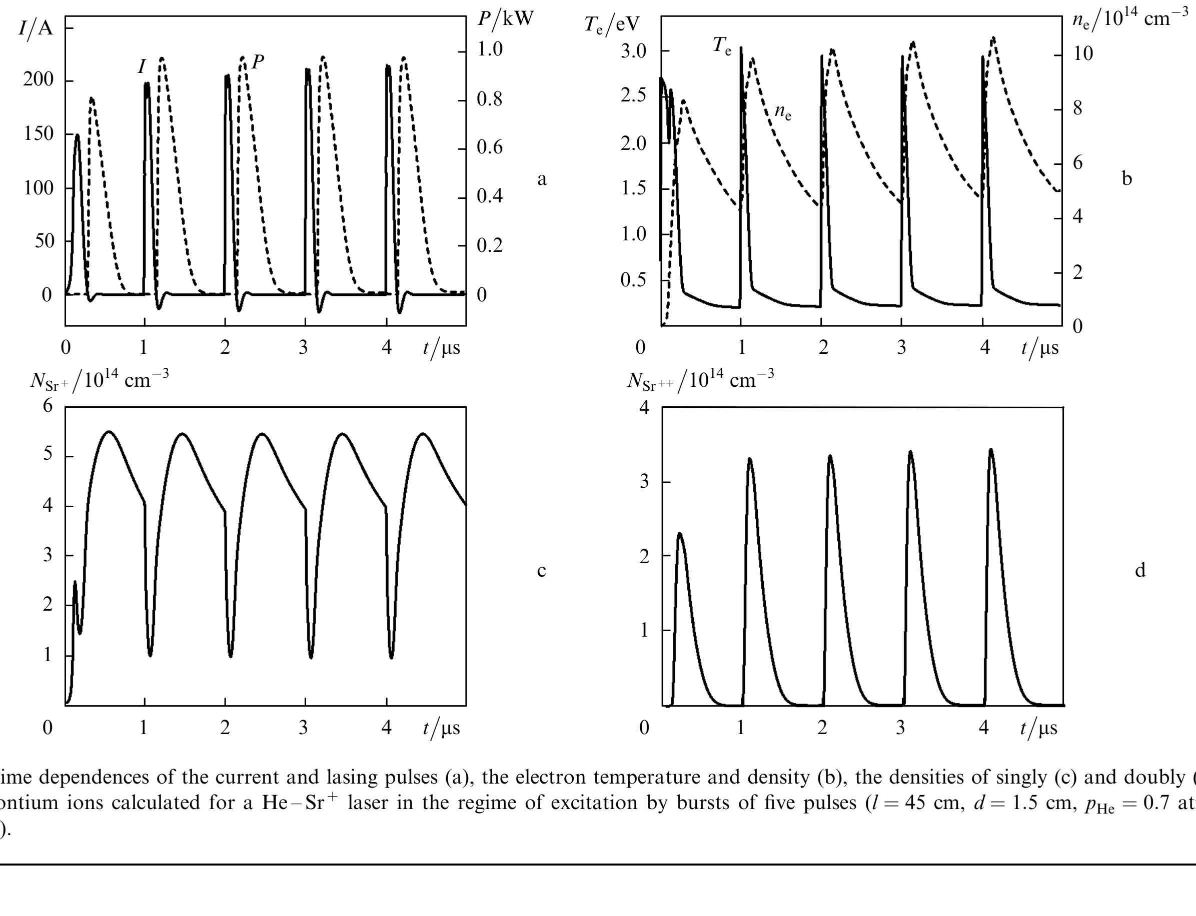

Figure 6. Time dependences of the current and lasing pulses (a), the electron temperature and density (b), the densities of singly (c) and doubly (d) charged strontium ions calculated for a $He-Sr^+$ laser in the regime of excitation by bursts of five pulses ($l = 45$ cm, $d = 1.5$ cm, $p_{He} = 0.7$ atm, $C = 825$ pF).

singly charged Sr^+ ions recombine much slower than the doubly charged ions Sr^{++}.

In the ordinary repetitively pulsed regime, the interpulse separation is rather long, so that the plasma manages to recombine almost completely by the beginning of the next excitation pulse. However, by shortening the interpulse interval substantially it is possible to increase the Sr^{++} ion production efficiency in the second and subsequent excitation pulses due to the ionisation of the Sr^+ ions that had no time to recombine, and hence to improve the He – Sr^+ laser energy characteristics.

Experiments with twin-pulse excitation [1, 2, 8, 25] showed that the pulse repetition rate in recombination lasers may in principle be quite high and range up to ~1 MHz, when the next excitation pulse does not yet overlap with the laser pulse. In this case, the energy gain in the second laser pulse in comparison with the first one may amount to 30 % – 40 %. This is close to the highest possible (~ 51.6 %) energy gain in the second pulse, which is equal to the ratio between the first ionisation potential of strontium (5.69 eV) and the second one (11.03 eV).

In the self-heating regime the power consumed by the active element, which determines its temperature and metal vapour density, must be constant, and therefore the shortening of the interpulse interval has to be realised in the regime of active-medium excitation by pulse bursts. For the thermal regime to be invariable under pulse-burst excitation, the relation $f_b = f/n_b$ should be fulfilled, where f_b is the pulse-burst repetition rate, n_b is the number of pulses in a burst, and f is the pulse repetition rate in the ordinary lasing regime.

We performed numerical simulations of the regime of He – Sr^+ laser pumping by pulse bursts with an interpulse interval of 1 μs. The optimal energy input was automatically determined in the simulations and corresponded to efficiency and average-power maxima.

Figure 6 shows the simulation data for the regime of excitation by bursts of five pulses. One can see that in the second and subsequent laser pulses there occurs an increase in pulse energy and peak power compared to the first pulse (Fig. 6a), which is due to the growth of the doubly charged Sr^{++} ion density (Fig. 6d). This growth is caused by the ionisation of the singly charged Sr^+ ion that had no time to recombine (Fig. 6c), and with retention of the low level of T_e in the afterglow (Fig. 6b) this leads to a growth of the pumping rate and the population inversion.

According to the calculations, in the second pulse the laser pulse energy increased by ~37 % and the peak power by ~19 %. These data are consistent with the data of experiments with twin excitation pulses [1, 2, 25].

Figure 7a shows the variation of efficiency within a long burst of 20 pulses. One can see that the efficiency peak is achieved in the pulses with numbers $n \sim 5 - 8$; in this case, it is approximately 39 % higher than the efficiency in the first pulse and 25 % than the efficiency in the ordinary lasing regime. In the subsequent pulses there occurs a lowering of the efficiency due to a growth of the gas temperature.

Figures 7b and 7c show the results of calculations of the efficiency averaged over pulse bursts and average laser power for burst with $n_b = 2 - 20$. Clearly in short bursts ($n_b < 10$) the effect of the lower first-pulse efficiency on the average efficiency is still significant, and therefore the average output power increases with increasing the number of pulses in a burst up to $n_b \sim 10$, and then there occurs power saturation followed by a slow decrease. The calculations suggest that the gain in efficiency and average output power under excitation by bursts with the optimal number of pulses $n_b \sim 10$ is equal to ~21 % in comparison with the ordinary repetitively pulsed regime.

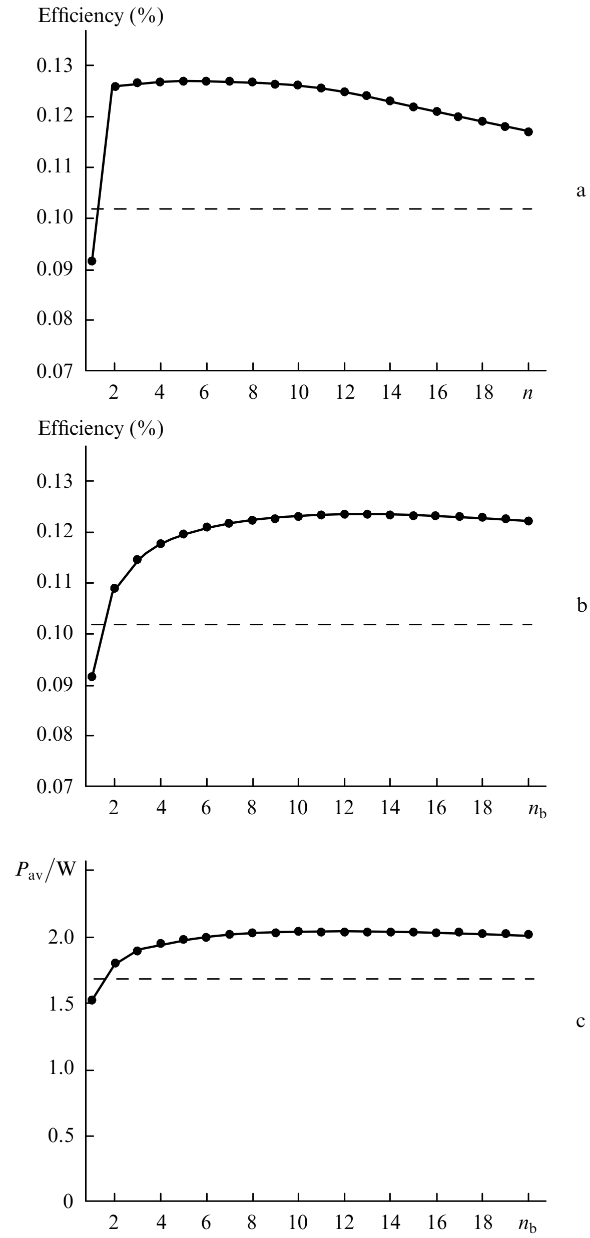

Figure 7. Calculated efficiency in different pulses of a burst (a) as well as averaged efficiency (b) and averaged output power of a He – Sr^+ laser (c) for bursts comprising different numbers of pulses; dashed lines – ordinary lasing regime (l = 45 cm, d = 1.5 cm, p_{He} = 0.7 atm, C = 825 pF).

5. Conclusions

We have performed a comprehensive analysis of the physical mechanisms which limit the growth of the energy characteristics of He – Sr^+ recombination lasers with increase in the active-medium pressure, the active volume, and the pulse repetition rate. It has been determined that the existence of optimal pressure is related to the limitation of electron cooling rate at high pressures due to the heating action of the trailing edge of a current pulse. We have shown that the average output power at high pressures may be raised by lowering the storage capacitance and inductance of the laser tube as well as by an abrupt termination of current pulse. With increase in tube diameter and pulse repetition rate, the average output power has been found to saturate and then to lower due to the formation of a radially nonuniform active medium as well as due to the growth of the electron temperature in the afterglow caused by the growth of the gas temperature. It has been shown that the possible ways of raising the output power are the blackening of the surface of a laser tube, the increase in its external diameter, an independent introduction of the vapour, and forced cooling, while the use of a tube of rectangular cross section will allow maximising the energy characteristics. Calculations with the use of a mathematical model showed that the attainable maximum of the linear output power of $He-Sr^+$ lasers amounts to $\sim$6.2 W m^{-1} for self-heating active elements of BeO ceramics and to $\sim$7.8 W m^{-1} with their surface blackening, to $\sim$7.7 W m^{-1} for an independent introduction of the metal vapour and to $\sim$9.4 W m^{-1} in combination with blackening, to $\sim$17 W m^{-1} for an intense forced cooling of cylindrical active elements and to $\sim$29 W m^{-1} with the active elements of rectangular cross section for a wall dimension ratio of 1 : 3. The feasibility of increasing the output power by approximately 21 % under excitation of the active medium by pulse bursts with a short interpulse interval has been demonstrated.

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