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Strontium vapour laser with ionisation and recombination mechanisms of inversion formation

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Abstract. **We have experimentally and numerically investigated a multiwavelength strontium vapour laser which simultaneously emits both in the IR spectrum range on the self-terminating transitions in strontium atoms and ions (λ = 6.456 and ~3 μm for Sr I, and $\lambda \approx$ 1 μm for Sr II) and in the visible range on the recombination transition in strontium ions (λ = 0.4305 μm for Sr II). A number of regularities in the behaviour of the output characteristics of lasing, which allow for a targeted search for optimal excitation conditions of the multiwavelength strontium vapour lasers, are established.**

Keywords: *strontium vapour laser, regime of simultaneous generation at several wavelengths, self-terminating transition, recombination transition.*

A self-heating, repetitively pulsed strontium vapour laser is an efficient source of coherent radiation in the IR range of the spectrum on self-terminating transitions in strontium atoms and ions (λ = 6.456 and ~3 μm for Sr I and $\lambda \approx$ 1 μm for Sr II) [1–7]. In addition, this laser emits with high efficiency in the visible spectrum range on the recombination transitions in strontium ions (λ = 0.4305 and 0.4162 μm for Sr II) [1, 2, 6–12]. At the same time, there is a possibility providing lasing simultaneously in the IR and visible spectrum ranges at several wavelengths (i.e. the multiwavelength lasing regime) at the expense both of ionisation and recombination mechanisms of the inversion formation [1, 2, 13]. In this case, a strontium vapour laser can be used as a source of multiwavelength radiation for the applied and scientific purposes. Thus, the realisation of recombination lasing regime ensures visualisation of IR radiation from the strontium vapour laser; in other words, visible radiation on the recombination transitions (λ = 0.4305 and 0.4162 μm for Sr II) can be considered as a visualizer of a bunch of IR radiation from the strontium vapour laser [13].

In the studies on metal vapour lasers, along with experimental methods, mathematical modelling methods are widely used, which can be useful in solving the problem of searching for optimal conditions of the excitation of active media, determination of the achievable lasing parameters, revealing the physical mechanisms describing the regularities which are experimentally observed [6, 11, 12, 14–16].

The aim of the present work is experimental and numerical studies of the strontium vapour laser to determine the excitation conditions providing efficient multiwavelength lasing on the self-terminating and recombination transitions in strontium atoms and ions.

In our experiments to study multiwavelength lasing, we have used a self-heating laser tube, the discharge channel of which was made of a BeO ceramic tube with a length l = 50 cm and an internal diameter d = 1.5 cm. Electrodes were located at the end faces of the discharge channel in the 'cold' buffer zones of the tube. The output window of the laser tube was made of calcium fluoride. As a highly reflecting mirror of the resonator, a mirror with an aluminium coating was used, while the output mirror represented a plane-parallel plate of calcium fluoride or a quartz plate with a dielectric coating for the region $\lambda \approx$ 0.43 μm. The current pulses and lasing were recorded using a current shunt and a coaxial FEK-24 photocell, respectively. The signals recorded by sensors were fed to a Tektronix TDS-3032 oscilloscope. The average lasing power was controlled by an OPHIR power meter (Nova II). To highlight various spectral components in the measurements of the lasing power, the SZS-20 and SZS-8 filters transmitting radiation in the regions $\lambda \approx$ 1 and ~3 μm, respectively, were used.

As a result of the research, simultaneous multiwavelength lasing was obtained in the IR and violet regions of the spectrum on six Sr I transitions: $5s5p^1P_1^0 - 5s4d^1D_2$ (λ = 6.456 μm), $5s4d^3D_1 - 5s5p^3P_2^0$ (3.066 μm), $5s4d^3D_2 - 5s5p^3P_2^0$ (3.011 μm), $5s4d^3D_3 - 5s5p^3P_2^0$ (2.92 μm), $5s4d^3D_2 - 5s5p^3P_1^0$ (2.69 μm), and $5s4d^3D_1 - 5s5p^3P_0^0$ (2.6 μm), and three Sr II transitions: $4p^65p^2P^0_{3/2} - 4p^64d^2D_{5/2}$ (1.033 μm), $4p^65p^2P^0_{1/2} - 4p^64d^2D_{3/2}$ (1.091 μm), and $4p^66s^2S_{1/2} - 4p^65p^2P^0_{3/2}$ (0.4305 μm) (see the simplified scheme of laser transitions in Fig. 1).

Experiments have shown that the Blumlein scheme is optimal for the active medium excitation. This scheme provides a steepness of both leading and trailing edges of the current pulse, which is necessary for efficient lasing on the self-terminating and recombination transitions in strontium.

Figure 2 shows typical waveforms of the current pulses through the laser tube (having an amplitude of 100–200 A), and also of lasing pulses at $\lambda \approx$ 1 and 0.4305 μm for Sr II. It can be seen that the lasing on self-terminating Sr II transitions (and also on the Sr I transition) occurs on the stage of the current rise. After the current pulse is terminated, a recombination lasing line (λ = 0.4305 μm for Sr II) is observed; in this case, a certain mismatch leads, as can be seen from Fig. 2, to the presence of small current oscillations at the stage of early

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afterglow, thus causing a nonmonotonic decline of the laser pulse (due to a significant dependence of the rate of recombination pumping on the electron temperature at the afterglow stage), which, however, does not affect significantly the energy performance of lasing.

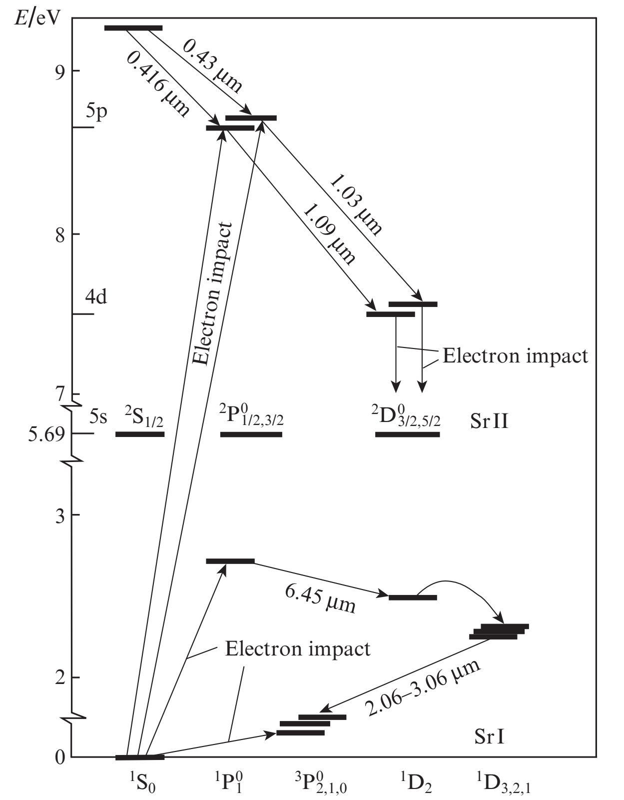

Figure 1. Simplified energy level diagram of the strontium atom and ion.

Studies have shown that the combined lasing on self-terminating and recombination transitions in strontium is observed in a fairly wide range of partial pressures of the working mixture components in the frame of the selected excitation scheme. As a buffer gas, we have used helium or its mixture with neon. The optimal buffer gas pressure for multi-wavelength lasing was 100–300 Torr, small additions of helium to neon ($p_{Ne} \leqslant 15$ Torr) having virtually no effect on the lasing characteristics (but facilitated the discharge ignition in the 'cold' tube), while with large supplements of neon, the energy characteristics at $\lambda = 0.4305$ μm for Sr II were deteriorated due to a decrease in the cooling rate of electrons at the afterglow stage in elastic collisions with heavy atoms and neon ions.

The partial pressure of strontium was determined by the tube wall temperature defined in the self-heating regime in accordance with the power consumed by the tube, which was optimised by varying the capacitance of the storage capacitors in the Blumlein scheme ($C_1 = C_2 \approx 1000-1600$ pF), the voltage of the high-voltage rectifier ($U \approx 3.5-7$ kW), and also the pulse repetition rate ($f \approx 5-15$ kHz). The operating temperature range for the lasing at $\lambda = 0.4305$ μm was 560–620 °C, while for the lasing at λ = 6.456, ~3 and ~1 μm, this range stretched to about 700 °C and above.

When varying the excitation conditions, the average lasing power for different spectral components in combined lasing was varied in the following ranges: $P_{av}(0.4305\ \mu m) \approx 0.05-0.3$ W, $P_{av}(6.456\ \mu m) \approx 0.4-1.25$ W, $P_{av}(\sim 3\ \mu m) \approx 0.05-0.45$ W, $P_{av}(\sim 1\ \mu m) \approx 0.05-0.2$ W. As example, Fig. 3 shows the dependence of these powers on the helium pressure at $p_{Ne} = 15$ Torr. The dependence of the average lasing power on the strontium vapour pressure is illustrated by the data in Table 1, which shows the output characteristics of multiwavelength lasing at $p_{He} = 120$ Torr, $p_{Ne} = 15$ Torr, $C_1 = C_2 = 1150$ pF, $f = 8$ kHz for two steady-state excitation regimes that differ in the voltage of the high-voltage rectifier U and, hence, in the temperature and power consumed by the tube. The first of these regimes (U = 5.6 kV) complies with the conditions of a

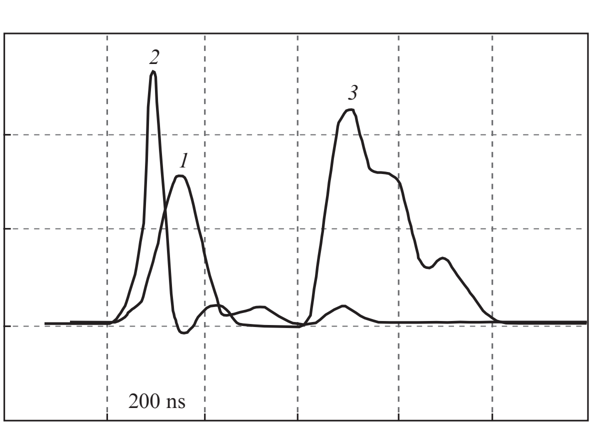

Figure 2. Typical waveforms of current pulses through the laser tube (*1*) and lasing at $\lambda \approx 1$ (*2*) and 0.4305 μm (*3*) for Sr II.

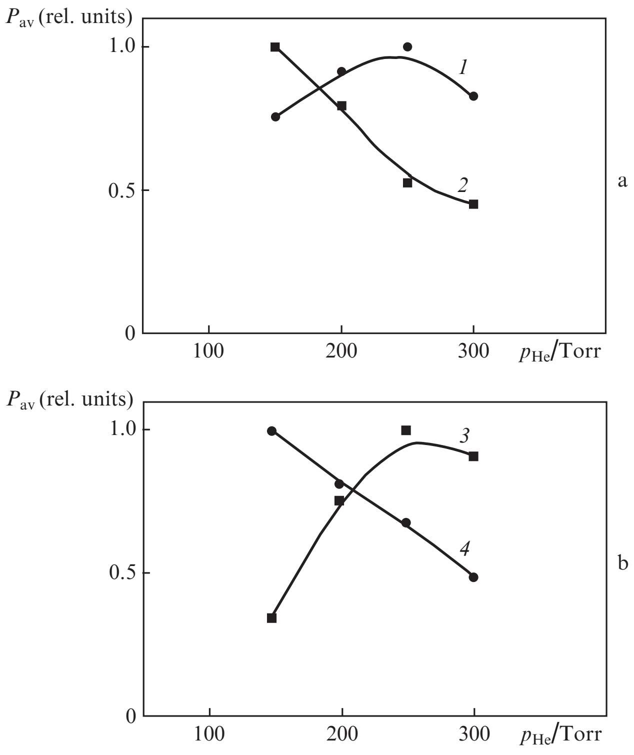

Figure 3. Average lasing power P_{av} as a function of helium pressure at (a) λ = (*1*) 0.4305 and (*2*) ~1 μm in Sr II and at (b) $\lambda \approx$ (*3*) 3 and (*4*) 6.456 μm in Sr I.

Table 1. Output characteristics of the multiwavelength lasing on transitions in Sr I and Sr II.

U/kV	P_{av}(6.456 μm)/W	P_{av}(~3 μm)/W	P_{av}(~1 μm)/W	P_{av}(0.4305 μm)/W	P^{Σ}_{av}/W
5.6	0.7	0.35	0.15	0.30	1.5
5.8	0.9	0.45	0.20	0.25	1.8

maximum average lasing power at λ = 0.4305 μm [P_{av}(0.4305 μm) = 0.3 W], while the second (U = 5.8 kV) – with the conditions of a maximum total average power P^{Σ}_{av} on the transitions Sr II and Sr I in the visible and IR spectrum ranges (P^{Σ}_{av} = 1.8 W). It is seen that at $U > 5.6$ kV, the lasing power in the visible region is reduced with increasing voltage and, as a consequence, with increasing temperature and strontium vapour pressure, while the power of IR lasing increases.

To carry out numerical experiments, in this study we have used a mathematical model of an ion He–Sr laser [15] comprising a joint description of the electrical circuit of pumping, plasma of a repetitively pulsed discharge, and laser radiation on the Sr II transitions in the visible and IR ranges of the spectrum. By using this model, we have conducted a numerical search for the regimes of the active medium excitation of the ion He–Sr laser, providing a possibility of efficient combined lasing on recombination (λ = 0.4305 μm) and self-terminating (λ = 1.033 and 1.091 μm) transitions in the strontium ion.

Figure 4 presents the calculated pulses of current and lasing on the lines with λ = 0.4305, 1.033 and 1.091 μm, the shape of which is consistent with the experimental waveforms (Fig. 2) and is typical for the ion He–Sr laser [1, 2]. From Fig. 4b, which shows the results of calculations of the concentrations of atoms, singly and doubly ionised strontium ions, it is clear that during the current pulse, a significant double ionisation of strontium occurs as a result of direct and stepwise ionisation by the electron impact. This ensures intensive recombination pumping of the levels of strontium ions and lasing on the line λ = 0.4305 μm at the early afterglow stage (Fig. 4a). Recombination pumping, the rate W_r of which strongly depends on the electron temperature T_e ($W_r \propto T_e^{-9/2}$ [1, 2, 6–9]), is 'switched' at the afterglow stage after a rapid decrease in T_e (Fig. 4c), which occurs due to elastic collisions of electrons with atoms and ions of helium – a light buffer gas. At the leading edge of the current pulse, as a result of excitation by the electron impact, the population inversion and lasing on self-terminating transitions with λ = 1.033 and 1.091 μm are observed (Fig. 4a).

Figure 5 shows the dependences of the average lasing power at the transitions with λ = 0.4305 and 1.091 μm on the helium pressure, calculated in accordance with the mathematical model. It is seen that this model accurately reflects the main peculiarities in the behaviour of the average lasing power of the ion He–Sr recombination laser both in recombination and ionisation regimes of pumping (see Fig. 3a). As follows from the results of numerical modelling, efficient combined lasing on the transitions in strontium ions in the visible and IR spectrum regions is possible in a fairly wide range of conditions.

On the basis of the simulation results, it is found that an increase in the helium buffer gas pressure leads to a monotonous decrease in the average lasing power on self-terminating transitions in strontium ions (Fig. 5), which is stipulated by a decrease in electron temperature during the current pulse and the corresponding decrease in the rate of electron-impact excitation of the resonant Sr II levels (which are the upper laser levels) at the leading edge of the current pulse.

For recombination transitions in strontium ions, the average lasing power increases with increasing helium pressure up to the optimal values of several hundred Torr. With a further increase in pressure, it decreases (Fig. 3a). An increase in the average power with increasing pressure is due to an increase in the lasing pulse energy, associated with accelerated cooling of electrons in elastic collisions with atoms and ions of helium and the corresponding increase in the rate of recombination

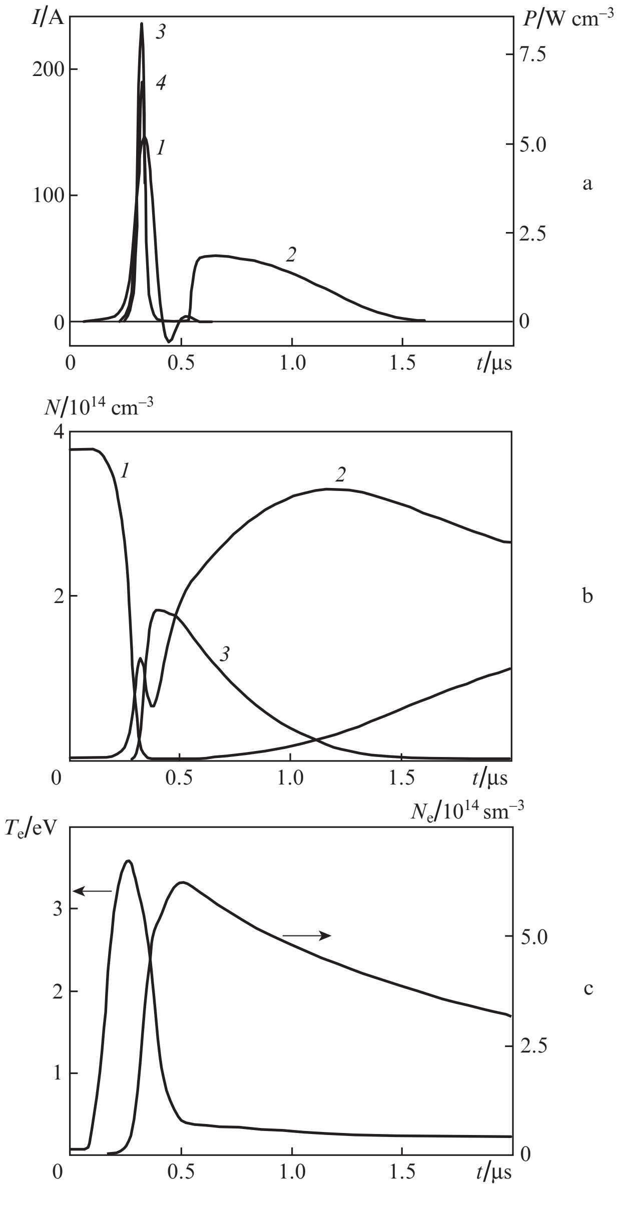

Figure 4. Calculated time dependences of (a) current pulses I and (1) lasing (P) for λ = (2) 0.4305, (3) 1.033 and (4) 1.091 μm in Sr II, (b) concentrations of N atoms (1), singly (2) and doubly (3) ionised ions of strontium and (c) concentration N_e and electron temperature T_e in the active medium of a strontium vapour laser at l = 50 cm, d = 1.5 cm, $C_1 = C_2$ = 1150 pF, p_{He} = 250 Torr.

pumping of Sr II levels. A decrease in the average power at high helium pressures is mainly caused by limitation of the cooling rate of electrons at the early afterglow stage due to heating at the trailing edge of the current pulse, which manifests itself when the cooling time of electrons, which diminishes with the pressure growth, becomes comparable with the trailing edge duration of the current pulse [1, 2].

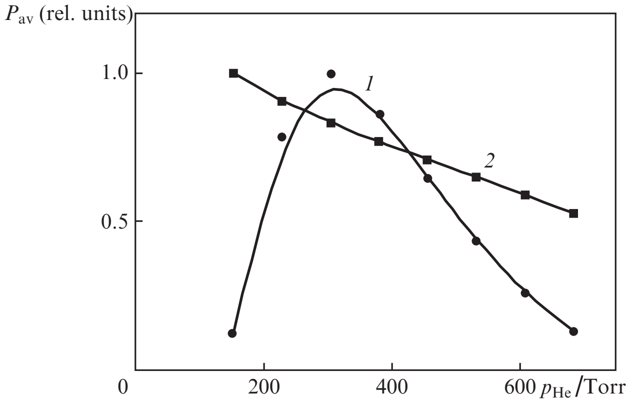

Figure 5. Calculated dependences of the average lasing power at λ = (*1*) 0.4305 and (*2*) 1.091 μm in Sr II on helium pressure at l = 50 cm, d = 1.1 cm, $C_1 = C_2$ = 1150 pF.

Thus, in the strontium vapour laser, simultaneous multiwavelength lasing in the IR and visible spectrum regions on the self-terminating and recombination transitions in strontium atoms and ions at λ = 6.456, ~3, ~1 and 0.4305 μm has been obtained and investigated. On the basis of experimental and numerical studies, we have found that this multiwavelength lasing is possible in a wide range of conditions. A number of regularities in the behaviour of the output characteristics of lasing have been established, and the physical mechanisms that determine these regularities have been revealed. This allows us to rely on the implementation of a strontium vapour laser with higher power characteristics by increasing the active medium volume. The results of this work offer an opportunity of a targeted search for the optimal excitation conditions for the multiwavelength strontium vapour lasers, and allow prediction of the development of such lasers with new performance characteristics.

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