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MULTIWAVELENGTH STRONTIUM VAPOR LASERS

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Based on an analysis of experimental and theoretical works, modern notion on conditions of forming of population density inversion on self-terminating IR transitions of alkali-earth metals is given. It is demonstrated that there is a significant difference in the inversion formation in lasers on self-terminating transitions in the visible and near-IR ranges and lasers on self-terminating transitions of alkali-earth metals lasing IR lines in the mid-IR range. It is shown that in the discharge circuit of lasers on self-terminating metal atom transitions (LSMT) there are processes strengthening the influence of the known mechanism limiting the frequency and energy characteristics (FEC) of radiation caused by the presence of prepulse electron concentration. The mechanism of influence of these processes on FEC of the LSMT and technical methods of their neutralization are considered. The possibility of obtaining average lasing power of ~200 W from one liter volume of the active medium of the strontium vapor laser is demonstrated under conditions of neutralization of these processes.

Keywords: strontium vapor laser, lasers on self-terminating transitions of metal atoms.

INTRODUCTION

By the present time lasing of coherent radiation has been excited in a variety of active media on many thousands of laser transitions with application of different methods of laser level pumping and mechanisms of forming a population inversion. However, despite an abundance of laser lines, a relatively small number of lasers are widely used mainly due to their high efficiency, good energy parameters, acceptable exploitation characteristics, required lasing wavelength range, etc. A list of photonics technologies crucial for Russia (according to “Strategic Program on Photonics and Its Applications” developed by the Russian Industry and Trade Ministry in 2014) includes the item “Effective Lasers of the mid-IR Range,” which indicates the urgency of investigations aimed at creation of effective lasers in the mid-IR range.

The investigations whose results are presented in this review have demonstrated the possibility of increasing by an order of magnitude of the average lasing power and efficiency of pumping of the active medium of a strontium vapor laser by decreasing the energy consumed to form the population inversion with the corresponding increase of the lasing pulse repetition frequency (PRF). The strontium vapor laser belongs to the class of lasers on self-terminating metal atom and ion transitions (LSMT) [1–4] which till now are the most effective sources of coherent radiation in the visible range of the spectrum among the gas lasers. For this reason, at present the copper vapor laser as radiation sources in the visible range of the spectrum (λ = 510.6 and 578.2 nm) are best studied. In the strontium vapor laser lasing is excited in the near- and mid-IR ranges on the $5s5p\,^1P^0$–$5s4d\,^1D_2$ SrI (λ = 6.456 μm), $5s4d\,^3D_1$–$5s5p\,^3P^0_2$ SrI (λ = 3.0665 μm), $5s4d\,^3D_2$–$5s5p\,^3P^0_2$ SrI (λ = 3.0111 μm), $4p^65p\,^2P^0_{1/2}$–$4p^64d\,D_{3/2}$ SrII (λ = 1.0917 μm), $4p^65p\,^2P^0_{3/2}$–$4p^65d\,^2D_{5/2}$ SrII (λ = 1.0330 μm), $4d\,^3D_1$–$5p\,^3P^0_0$ SrI (λ = 2.60 μm), $4d\,^3D_2$–$5p\,^3P^0_1$ SrI (λ = 2.69 μm), and $4d^3D_3$–$5p^3P^0_2$ SrI (λ = 2.92 μm) self-terminating transitions. It should be noted [3–6] that lasing on transitions of triplet groups of (^3D–$^3P^0$) levels cannot be considered as *lasing on self-terminating transitions* in classical understanding, since the upper laser

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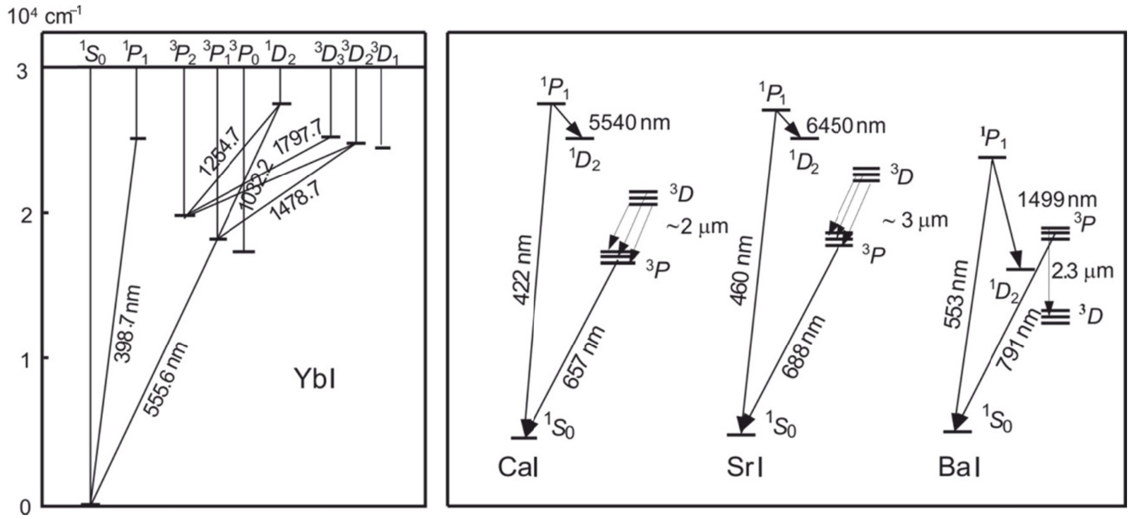

Fig. 1. Fragments of the structure of the lower levels of Yb, Ca, Sr, and Ba atoms.

levels are metastable. In original literature it is accepted to call it lasing on metastable-metastable or M-M transitions [3–7].

The inverse population density can be formed in lasers on self-terminating transitions only in the presence of ionized nonequilibrium plasma. During this period, the rate of excitation of the upper laser (resonant) level is much higher than of the lower (metastable) level. Indeed, because of the high electronic temperature (T_e), the rate constant of upper laser level excitation is greater than the rate constant of lower level excitation for two reasons. First, the maximal effective cross section of atomic energy level excitation by the first-order electron impacts is observed, as a rule, for exciting electron energies (3–4)E_i, where E_i is the energy of the ith level. Second, the effective excitation cross section of the energy level by the first-order inelastic electron impact via optically forbidden transitions is lower than via allowed transitions. Thus, the basic mechanism of LSMT lasing is a higher rate of excitation of the upper laser level in comparison with the lower level by electron impacts in the presence of the ionized nonequilibriun plasma of the pulsed gas discharge, and the population density inversion is formed by the three-level scheme. The presence of the triplet group of (^3D–$^3P^0$) levels in strontium influences significantly the mechanism of forming the population density inversion in the active medium of the strontium vapor laser [8] and causes a significant difference of the frequency and energy characteristics of radiation from the observed FEC dependence of LSMT radiation in the visible range, which necessitates investigations of the strontium vapor laser.

1. SPECIAL FEATURE OF FORMING THE POPULATION DENSITY INVERSION ON SELF-TERMINATING IR TRANSITIONS OF ALKALI-EARTH METALS

Ph. Cahuzac [9–11] observed many superluminosity lines and pulsed lasing in the near- and mid-IR ranges of the spectrum exciting the mixture of vapors of alkali-earth metals (AEM) Ca, Sr, and Ba and rare-earth metals (REM) Yb, Tm, Sm, and Eu with helium by a pulsed electric discharge. The strongest lasing lines of Ca, Sr, and Ba correspond to the ($^1P_1^0$–$^1D_2$) transitions from the first $^1P_1^0$ resonant level to the $^1D_2$ metastable level and other lasing lines between closely lying triplet levels (including those in Yb and Tm atoms) and start from the levels that are not optically bound with the ground state. Figure 1 shows fragments of the structure of the lower levels of the examined atoms. The structure of the excited states of the ytterbium atom is close to the typical spectrum of alkali-earth atoms due to the fact that these elements have completely filled valence s^2 shells.

It is well known that in stationary gas discharges with traditional chemical composition of the working mixtures (metal vapor + inert gas) there are at least two major challenges to the implementation of the continuous mode of lasing on transitions from resonant to metastable states: 1) lacking of predominantly selective excitation of the resonant state and 2) necessity of sufficiently fast relaxation of metastable particles. For AEM the $^1P_1$ resonant and $^1D_2$ metastable levels have relatively close values of excitation energies (see diagram of levels for SaI, SrI, and BaI in Fig. 1). Such structure of the excited states first, provides predominantly electronic excitation of resonant levels in comparison with metastable ones at electronic temperatures realized in the gas discharge plasma. It is important to note that this condition remains valid even at relatively low electronic temperatures realized in stationary discharges in metal vapors. Second, this eliminates the need for fast relaxation of the lower metastable working level, since the probability of radiative decay on the working IR transitions is insignificant and does not exceed 10^5–10^6 s^{-1} for Ca, Sr, and Ba atoms. Therefore, continuous lasing on self-terminating transitions of SaI and SrI in a mixture with hydrogen was excited in [12], and quasicontinuous lasing was excited in [13, 14] on the same transitions of SaI and VaI in a mixture with helium in narrow gas-discharge tubes. In this case, the mode of stationary population density inversion on transitions of these elements is sufficiently easily realized.

The difference in the inversion formation is determined by the fact that in the LSMT of the visible and near-IR ranges with quantum efficiency of working transition greater than 20 % there exists a certain value of the electronic temperature T_e at which the rate of upper laser level population starts to exceed the rate of lower laser level population (for example, ~1.7 eV for Cu). Hence, the working transitions of atoms start to be populated by groups of electrons with different energies, whereas in lasers with the quantum efficiency of working transition less than 20 % that radiate in mid- and far-IR ranges there are no threshold pumping conditions. In this case, all electrons participate in the formation of population densities on working transitions, and the inversion is determined by the ratio of the excitation cross sections of the working laser levels.

A reason for the occurrence of population density inversion and lasing on transitions between triplet levels of these elements, as demonstrated experiments with optical pumping of Yb vapors, is energy transfer from the $^1P_1^0$ resonant state to the ^3D_j lower laying triplet states in the process of collisions of metal atoms in the $^1S_0$ ground state with the excited metal atoms in processes of the type

$$\mathrm{Yb}(^1P_1) + \mathrm{Yb}(^1S_0) \Leftrightarrow \mathrm{Yb}(^3D_j) + \mathrm{Yb}(^1S_0) \pm \Delta E.$$

The measured rate constant of this process exceeds 10^{-8} cm^3/s. From the available experimental results it also follows that the population of the Yb(^3D_j) states in the process of collisions with helium is insignificant. A decrease in the fluorescence intensity from the $^1P_1$ ytterbium level with increasing NeI pressure under optical pumping is determined by broadening of the absorption line at $\lambda = 555.6$ nm in the process of collisions with helium atoms. Analogous process must be observed in AEM vapors proceeding from the structure of the lower levels of these atoms (see Fig. 1)

$$\mathrm{Sr}(^1P_1) + \mathrm{Sr}(^1S_0) \Leftrightarrow \mathrm{Sr}(^3D_j) + \mathrm{Sr}(^1S_0) \pm \Delta E,$$

$$\mathrm{Sr}(^1D_2) + \mathrm{Sr}(^1S_0) \Leftrightarrow \mathrm{Sr}(^3D_j) + \mathrm{Sr}(^1S_0) \pm \Delta E.$$

As demonstrated experiments on optical pumping of Yb vapors and mutual arrangement of the lower energy levels of the AEM and REM atoms, there is a possibility of energy transfer from the excited resonant and metastable levels to closely located lower-lying triplet levels via radiative and nonradiative (collision) processes.

The $^1D_2$ metastable states of AEM and REM atoms also decay in the analogous processes of collision deactivation with metal atoms in the ground state as well as in the process of collisions with electrons under conditions of gas discharge. Such mechanism of excitation of working laser levels in AEM and REM vapors is typical and is analogous to the four-level scheme of forming the population density inversion and excitation of the upper working levels in the solid-state lasers, for example, in a neodymium laser under optical pumping. The aforesaid necessitates a more detailed study of alkali-earth metal vapor lasers, in particular, the strontium vapor laser as a most multiwavelength source of coherent radiation in the near- and mid-IR ranges from the above-listed group of lasers.

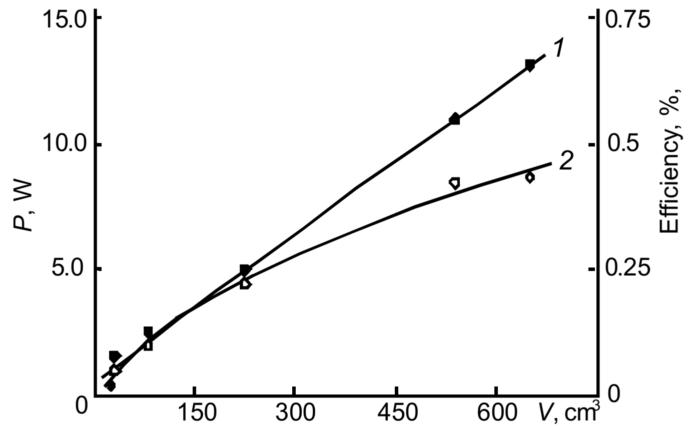

Fig. 2. Dependence of the average lasing power (curve *1*) and efficiency (curve *2*) of the strontium vapor laser on the volume of the active medium.

2. FREQUENCY AND ENERGY CHARACTERISTICS OF LASING

2.1. Volume scaling of the strontium vapor laser

In [15] it was experimentally demonstrated that an increase in the volume of the active medium of the strontium vapor laser is accompanied by the corresponding increase of the average lasing power and efficiency. From the active element with a volume of 220 cm^3, an average lasing power of 5.5 W was obtained. Thus, the behavior of the average lasing power obviously demonstrated the possibility of its further increase by increasing volume of the active medium. Therefore, the Sr laser with working volumes of 540 and 650 cm^3 was investigated in [16]. The experimentally observed dependence of the average lasing power and efficiency on the volume of the active medium is shown in Fig. 2. This dependence is linear in character, namely, the lasing efficiency increases with the volume of the active medium and becomes comparable with the efficiency of the copper vapor laser (0.45 %). A total average lasing power of ~13.5 W was obtained for the gas-discharge tube (GDT) with a volume of 650 cm^3 when the mixture of He and Ne gases in the ratio ~10/1 was used as a buffer gas.

An important characteristic of radiation is the distribution of the lasing power over the diameter of the discharge channel. This characteristic testifies to a complete use of the working volume. In [16] the discharge channel diameters *d* were 25 and 30 mm for volumes of 540 and 650 cm^3, respectively. This distribution is shown in Fig. 3*a* for average lasing powers of ~4.6, 7.4, and 9 W, respectively. Radiation at a level of half-amplitude of the lasing power occupied 65 % of the entire working region or 80 % of the diameter. The distribution was recorded using a Fabry–Perot resonator. An increase in the lasing power to 9 W did not change significantly the pattern of the lasing power distribution over the discharge channel diameter. The radiation distribution over the beam diameter was measured for the (He + Ne) buffer gas at a pressure of ~100 Torr. An increase in the buffer gas pressure to 250 Torr (Fig. 3*b*) demonstrated that radiation was concentrated in the paraxial region of the discharge channel of the GDT, and the radiation distribution over the cross section of the discharge channel became more non-uniform in character.

The uniform radiation distribution over the diameter of the discharge channel of the laser GDT suggests the possibility of increasing the average lasing power by means of increasing the volume of the active medium.

2.2. Limiting pulse repetition frequency for lasers on self-terminating transitions of strontium atom and ion

The most efficient among the LSMT is the copper vapor laser; plenty of publications (for example, see [1, 2]) are devoted to its investigation. Among the factors limiting the attainable PRF of the copper vapor laser are a high

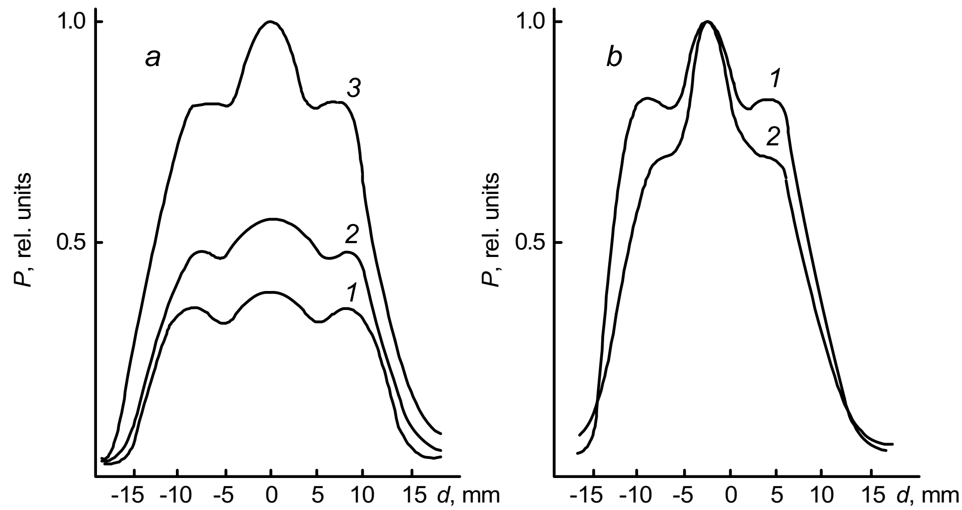

Fig. 3. Distribution of the power of strontium vapor laser radiation over the diameter of the active volume in a plane-parallel resonator: *a*) lasing power of 4.6 (curve *1*), 7.4 (curve *2*), and 9 W (curve *3*) and channel diameter of 30 mm; *b*) for buffer gas (He and Ne mixture) pressures of 100 (curve *1*) and 250 Torr (curve *2*).

prepulse population density of metastable states and a high prepulse electron concentration; in this case, different factors are interrelated [17], and their contribution depends on the conditions and methods of excitation of the active medium [18]. The ambiguity in estimated achievable FEC in the literature demonstrates the necessity of further investigations aimed at elucidation of the energy potential of lasers on self-terminating transitions, including the strontium vapor laser.

Experimental investigations of the FEC of the strontium vapor laser (λ = 1.033 and 1.091 μm) by the method of application of an additional pulse before each excitation pulse [19, 20] and results of numerical modeling of the kinetic processes in the active medium demonstrated that with decreasing delay between the additional and excitation pulses (for comparable energies of pumping of both pulses), no changes were observed in the output pulse energy of the additional pulse for lasers on self-terminating transitions of both SrI atom and SrII ion. In this case, the output pulse energy of the laser on self-terminating SrI transitions in the exciting pulse fast decreased. At the same time, the lasing pulse energy of the laser on self-terminating SrII transitions increased for the excitation pulse delayed by a certain time. To illustrate the aforesaid, Fig. 4 shows the waveforms of current and lasing pulses for the laser on self-terminating IR SrII transitions (λ = 1.033 and 1.091 μm) in the presence of only one exciting pulse and for two-pulse excitation with additional and exciting pulses delayed by 2.6 and 1.35 μs, respectively.

Experiments [21] performed in the mode of excitation with a pulse train comprising three pulses delayed at ~1–3 μs showed that by analogy with recombination SrII laser transitions [22], the energy characteristics of the laser on self-terminating IR SrII transitions during the second and third pulses exceeded their values during the first pulse. To interpret these experimental results, the kinetics of the processes proceeding in the active medium was modeled numerically. Calculations were performed for a self-consistent mathematical model of the He–Sr^+ laser [23]. Modeling of the two-pulse excitation mode with pulse delays varying in wide limits showed that the maximum gain during the second pulse was observed with delays ~5–10 μs and exceeded several times the gain in the mode with one excitation pulse. With further increase in delays, the positive influence of the sufficiently high residual prepulse strontium ion concentration decreased and became insignificant for delays ≥30–50 μs. These results allowed the optimal PRF of ~100–200 kHz to be recommended for the pulse train mode and the principal feasibility of lasing on self-terminating IR SrII transitions in pulse-periodic mode with high PRF (~1 MHz) to be confirmed. In self-heating mode of strontium vapor laser operation with gas-discharge tube whose discharge channel is made of the BeO ceramic tube with inner diameter of 8 mm and working volume of 9 cm^3, lasing was experimentally observed with excitation PRF up to 830 kHz [24].

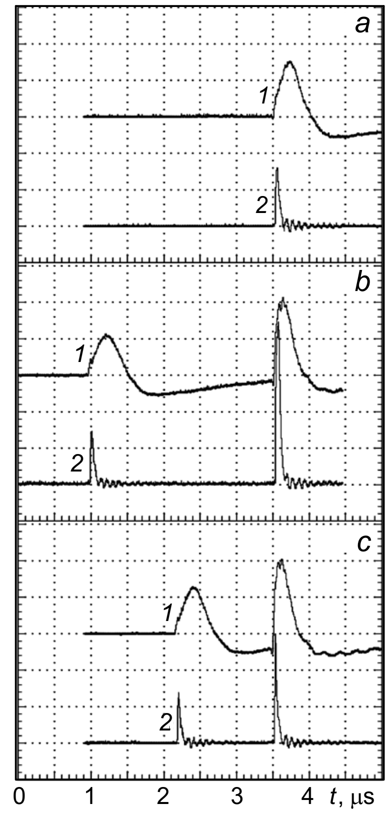

Fig. 4. Waveforms of the current (curve *1*) and lasing pulses (λ = 1.033 and 1.091 μm; curve *2*) of the laser on self-terminating IR SrII transitions in the presence of only the exciting impulse (*a*) and for two-pulse excitation with additional and exciting pulses delayed by 2.6 (*b*) and 1.35 μs (*c*). The abscissa for current pulses is 133 A/division.

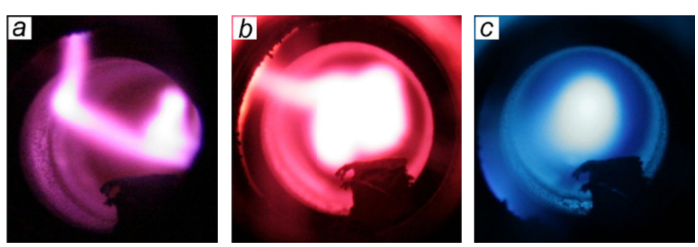

Fig. 5. Discharge formation during heating of the discharge GDT channel to the working temperature: *a*) contracted discharge (beginning of heating), *b*) beginning of the discharge decontraction (presence of metal vapors), and *c*) decontracted discharge at the working temperature.

Investigations of the energy characteristics of the strontium vapor laser demonstrated that the discharge had three stages during GDT heating (see Fig. 5). A contracted discharge (Fig. 5*a*) was observed in the initial heating stage. The discharge was decontracted when metal vapors penetrated into the active GDT volume (Fig. 5*b*). The diffuse discharge was observed at the working temperature of the discharge GDT channel (Fig. 5*c*). Exactly for the diffuse discharge the dependences of the energy characteristics of the Sr laser were observed that were not observed for the decontracted discharge. Subsequent investigations [25] demonstrated that in cold buffer zones (CBZ) of the gas-discharge tube a hindered discharge arises during charging capacitive elements from an accumulation capacitor when the electrodes in the gas-discharge tube were located in the cold buffer zones at distances ≤1–3 mm from the heat-insulated gas-discharge channel. In this case, after discharge ignition along the right branch of the Paschen curve during current growth accompanied by gas heating, a transition to the left branch of the Paschen curve occurred that eliminated the discharge contraction in the cold buffer zones and initiated a capacitive HF discharge in the active medium starting from the *breakdown* moment. The results obtained showed that the obtained FEC of radiation of the strontium vapor laser were caused not only by different modes of inversion formation in lasers on self-terminating transitions of visible and near-IR ranges and lasers on self-terminating transitions of alkali-earth metals, but also by the arrangement of electrodes in the gas-discharge tube.

The results presented above necessitate the performance of the whole complex of research of both gas discharge physics and electrophysical processes in the discharge circuit of the laser as well as of diagnostics of the active medium of the strontium vapor laser.

3. SPECTROSCOPIC DIAGNOSTICS OF THE ACTIVE MEDIUM OF THE STRONTIUM VAPOR LASER

Spectroscopic methods of research [26, 27] are most suitable for diagnostics of plasma evolution with time and space during several hundred nanoseconds. In [28] spectroscopic diagnostics of He–Sr and Ne–Sr lasers was performed using spatial division of plasma column radiation into central (CZ) and more peripheral (MPZ) radial zones. The most important plasma parameters – electron concentration n_e and electronic (T_e) and gas temperatures (T_g) – were determined for two radial zones at different time moments counted from the onset of the current pulse. The spectroscopic methods of determining the plasma parameters – T_e, n_e, and T_g – are based on measurements of absolute and relative intensities of spectral lines. A comparison of the time characteristics of radiation with the current-voltage characteristics (CVC) of the discharge demonstrated that the beginning of a sharp increase in the current and the maximum voltage on the GDT corresponded to the beginning of a sharp increase in the plasma radiation intensity. Time was counted from this very moment. In data processing, the spectral line intensities were measured at moments of their maximum intensities. Figure 6 shows the results of measuring T_e, n_e, and T_g for the Sr–Ne and Sr–He mixtures in the central and more peripheral zones.

From the results shown in Fig. 6 it can be seen that after the termination of the excitation pulse, the plasma parameters change very slightly for ~300–1000 ns and are leveled for the examined zones. This is most likely caused by the duration of the process of ambipolar diffusion. Plasma diagnostics for $t > 1$ μs was not performed, but by analogy with the results obtained for the copper vapor laser in the near afterglow [27], a repeated sharp decrease in T_e from 1 to 0.2 eV and in n_e from 10^{14} to 10^{13} cm^{-3} could be expected for the strontium vapor laser during 1–3 μs. These sharp changes of the parameters result in jumps of the intensity of some spectral lines during the above-indicated time period [28]. From Fig. 6 it can be seen that absolute values of T_e, n_e, T_g depend weakly on the buffer gas type. However, the buffer gas affects the velocity of plasma motion from the walls toward the center. Under identical conditions of excitation, the high-temperature plasma boundary in the stable thermal mode in neon could not reach the center of the tube, whereas in helium it approached the GDT center. There exists a hypothesis on the electric field motion from the walls toward the center in the laser on self-terminating transitions of metals atoms [29]; it is confirmed experimentally in the GDT whose diameter is greater than 4 cm [30, 31]. Probably, this effect is more pronounced in tubes with large diameter. In this work it was observed in the GDT 1.5 cm in diameter.

4. ELECTROPHYSICAL PROCESSES IN THE LSMT DISCHARGE CIRCUIT

According to the theory of electric circuits, to analyze the electrophysical process in an electric circuit, its equivalent circuit must be constructed. An analysis of the electrophysical processes in the LSMT discharge circuit was performed in [32] using the equivalent circuit [33] for the electric discharge circuits of the laser with gas-discharge tube in which electrodes were located in cold buffer zones (CBZ). The discharge evolution in such GDT design occurred

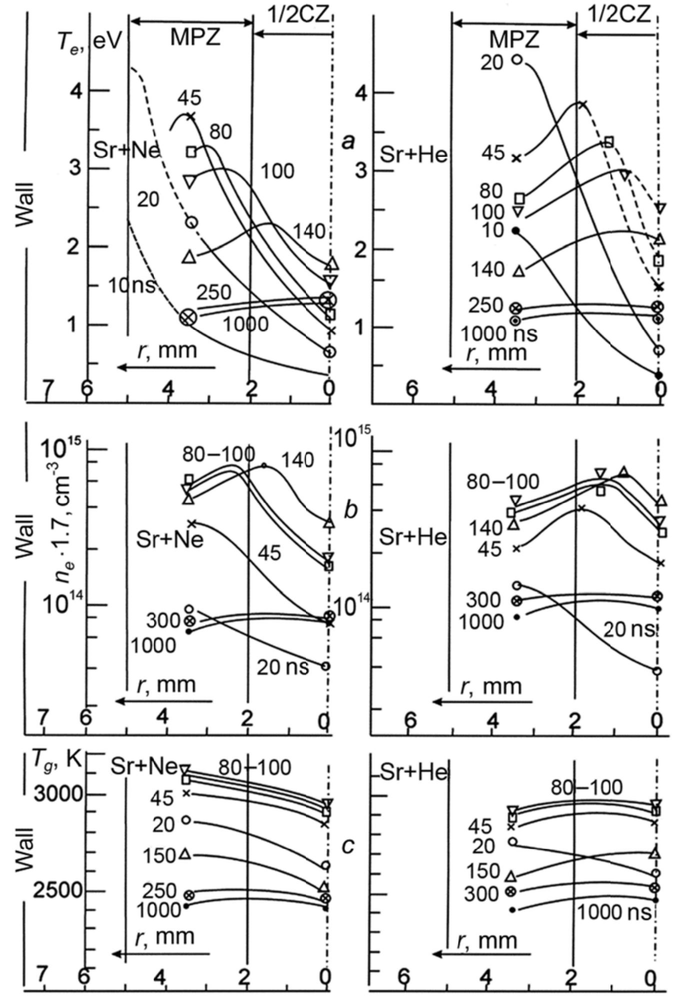

Fig. 6. Spatiotemporal dependences of T_e, n_e, and T_g for Sr–Ne and Sr–He lasers.

with the *breakdown* stage the presence of which was fist indicated in [34]. Results of investigations [32] demonstrated the presence of the preparatory stage before active medium pumping, during which capacitive elements of the discharge circuit were charged from the accumulation capacitor. As a result, three coupled pumping circuits were formed after breakdown, including the accumulation capacitor *C*, the peaking capacitor C_0, and the internal capacitor C_{GDT}. In this case, the commutator was placed outside of the pumping circuits formed by the capacitors C_0 and C_{GDT}. This provided the possibility of pumping of the active medium in the mode of high frequency of free oscillations under conditions of low allowable rate of current increase in thyratrons and eliminated the parasitic effect of population of metastable states on the excitation pulse front [35]. According to [25, 32], during charging the capacitive elements of the discharge circuit an anomalous glow discharge was ignited in the CBZ. The development of thermal instabilities led to a decreasing CVC and, as a consequence, to breaking of stable discharge burning. The discharge contraction was observed in the CBZ, the cathode spot fast heated, thermal emission was observed, and the CBZ resistance sharply decreased during a shot time period (until the *breakdown*). In this case, the CVC of the anomalous glow discharge in the CBZ developed along the right Paschen curve with strong growth of the current and sharp voltage decay. In this case, the *breakdown* actually indicated only the transition from the preparatory stage to pumping of the active medium (*pseudo breakdown*), since it was always observed in the maximum of the voltage amplitude on the GDT. Hence the given process called tentatively *the breakdown* is not the breakdown in its classical understanding.

Let us consider the process of charging C_0 and C_{GDT} from the accumulation capacitor taking into account the specific features of the C_{GDT} design. The active medium of the pulse-periodic LSMT is characterized by high plasma conductivity with the prepulse electron concentration $n_{eo} \sim 10^{13}$ cm^{-3}. In this case, the active medium, the discharge channel of the GDT, and the return current conductor represent the capacitor C_{GDT} in which the active medium is one of the capacitor plates. However, the plasma by the definition is quasi-neutral. Therefore, the excessive charge cannot be accumulated in the active medium during C_{GDT} charging. The excessive charge should be located on the surface of the ceramic discharge channel shunting the active medium during C_{GDT} charging, which is confirmed by the experimental results presented in [34], namely, by the absence of ionization and pumping of the active medium when the phantom current flows.

However, in actual practice of laser operation the residual prepulse plasma conductivity always exists in the CBZ because of incomplete recombination, and this conductivity the larger, the higher is the excitation PRF. Hence, C_0 and C_{GDT} are charged from C in the laser under conditions of shunting of the capacitive elements of the active element circuit in the CBZ from the side of the anode. This causes the voltage on the GDT to decrease and, as a consequence, leads to a redistribution of the population rates of laser levels in favor of metastable ones during pumping with increasing excitation PRF irrespective of the processes proceeding in the active medium. From the aforesaid it follows that the limitation on the LSMT energy characteristics arises already in the preparatory stage before pumping of the active medium.

Let us consider now the process of capacitive element discharge in the circuit, that is, directly the process of forming the inversion in the active medium. Three circuits are formed after charging of the capacitive elements: 1) C_{GDT}, 2) C_0, and 3) C. We now consider the contribution of each circuit to the inversion. The first circuit will have the highest frequency of free oscillations. As a result, the resistance of the CBZ from the anode side will practically vanish during C_{GDT} discharge, since the plasma volume in the CBZ makes ~1 cm^3 because of contraction of the discharge. This will lead to C_{GDT} shunting and occurrence of the potential difference in the active medium. Lasing in the LSMT under optimal excitation starts ~4–6 ns after the achievement of the maximal voltage amplitude on the GDT. In this case, the time of C_{GDT} discharge is ~4–10 ns, and the second and third circuits participate directly in pumping of the active medium of metal vapor lasers (MVL). It is obvious that the duration of the pumping pulse from the third circuit exceeds at least by three times the corresponding duration of the pumping pulse from the second circuit (since $C \sim 10\,C_0$) even in the ideal case in which the resistance of the open thyratron is negligibly small. Hence, the inversion formation in the active medium is determined by the second excitation circuit. The energy deposited from the second excitation circuit is ~10 % of the total energy deposited from the two pumping circuits that determines the low practical efficiency of MVL of ~1 %.

An analysis performed in [32] demonstrated that using the controllable commutator that should be closed after charging of the capacitive elements of the laser discharge circuit, the pumping efficiency can be increased to expected values by resonant charging of the capacitive elements from the accumulation capacitor under conditions of elimination of their shunting from the GDT anode during charging. The determining condition for increasing the FEC of the LSMT is elimination of shunting of the capacitive circuit elements during their charging, for example, providing the complete recombination of plasma in the CBZ from the side of the GDT anode. Neutralization of charges in the active LSMT medium, as is well known, is determined by three-particle volume recombination. The rate constant β_e of this process depends on the electronic temperature T_e, namely, $\beta_e \sim T_e^{-9/2}$. Neutralization of charges in the CBZ where metal vapors are absent is determined by the dissociative recombination whose rate increases with decreasing gas temperature. This determines the technical solutions used nowadays to increase the FEC of the LSMT [36], namely, circulation is performed through GDT mixtures buffer gas + HBr. Other technical solutions allowing shunting of capacitive elements to be eliminated and optimal lasing PRF of the copper vapor laser to be increased up to 16–30 kHz [37] are based on the application of the additional commutator – kivotron – connected into the laser discharge circuit from the side of the GDT anode that is quickly opened after charging of the capacitive elements. A technical solution of the problem is also neutralization of charges in the CBZ of the GDT due to their escape on the wall when the electrodes are arranged at distances of 1–3 mm from the discharge channel of the GDT [38]. In this case, in [20] it was experimentally shown that the application of the method of dual pulses allowed a lasing PRF of ~1 MHz to be attained for the strontium vapor laser with such GDT design. In the pulse-periodic excitation mode, a limiting lasing PRF of 830 kHz was obtained in [24]. The principal possibility of resonant charging of the capacitive elements from the accumulation capacitor was experimentally demonstrated in [39] for the strontium vapor laser after incorporation of an inductance of ~20 μH into the discharge circuit.

The experimental results presented above are the most evident illustration of the feasibility of technical implementation of effective active medium pumping in the strontium vapor laser considered in the present work in gas-discharge tubes with the electrodes located in the CBZ.

CONCLUSIONS

The presence of the triplet group of (^3D–$^3P^0$) levels in strontium influences significantly the mechanism of forming the population density inversion in the active medium of the strontium vapor laser, since the possibility exists of excitation energy transfer from the resonant and metastable levels to the closely and lower-lying levels as a result of radiative and nonradiative (collision) processes. In this case, the aforesaid does not explain completely the experimentally observed dependences of the energy characteristics of strontium vapor laser radiation on the pumping parameters. The observed dependences are determined to a greater extent by the technical solutions that changed the process of discharge formation in the active laser medium and make it possible to decrease the power spent for the formation of the population density inversion remaining the output energy unchanged. In the mode of *cutoff* of the third excitation circuit, an average lasing power of the strontium vapor laser can attain ~150–200 W from one liter volume of the active medium.

The LSMT have been investigated already for 50 years; however, it appeared that physics and mechanisms of forming the pulse-periodic discharge in active media with high plasma conductivity have been least understood. This can be demonstrated more clearly on the following example. It was always suggested that the electronic temperature in such discharges is determined by the element with the least ionization potential and that it was impossible to excite, for example, lasing on the self-terminating transitions of helium in a mixture of metal vapors with helium. However, we have excited lasing on self-terminating transitions of helium in the mixture Sr + He + Ne [38], and as demonstrated our investigations, its implementation is determined by the mechanism of discharge formation in the active medium. Hence, a study of physics and mechanisms of discharge formation in active media with high plasma conductivity will provide deeper understanding of the processes of forming the population density inversion in the LSMT and will allow us to estimate possible methods for realization of the energy potential of active media of these lasers.

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