About limiting pulse repetition rate of self-terminating He–Sr$^+$ laser

A.N. Soldatov,[1,2] N.A. Yudin,[1] A.V. Vasil'eva,[1,2] Yu.P. Polunin,[2] E.L. Latush,[3] G.D. Chebotarev,[3] and A.A. Fesenko[3]

[1] *West-Siberian Branch of Russian State University of Innovation Technologies and Enterprise, Tomsk*
[2] *Tomsk State University*
[3] *South Federal University, Rostov-on-Don*

Received March 27, 2008

Results of experimental research of frequency and energy characteristics of laser on self-terminating transitions in strontium ion (λ = 1.03 and 1.09 μm) by the method of introduction of an additional pulse before each excitation pulse and the results of theoretical calculations of parameters of He–Sr$^+$ laser active medium are presented. It is shown, that pulse repetition rate of self-terminating He–Sr$^+$ laser can reach ~1 MHz and the increase of pulse energy in a certain pulse-delay range is thus observed.

Introduction

One of the most efficient RM-laser (based on transitions from resonant to metastable level) is a copper vapor laser (CVL). A great part of publications describe the processes occurring in its active medium.[1–3] As is known, the inversion occurs in CVL only in the period of ionization nonequilibrium plasma on the leading edge of the excitation pulse, because in the following period (quasi-stationary ionization) each ionization act correspond to each act of upper laser level excitation.[1,4] This determines a series of interrelated causes of limitation of the CVL frequency and energy characteristics.

First, it stipulates the population saturation of upper laser levels in the excitation pulse, being a factor of the generation pulse energy limitation from above. Therefore, to obtain a high level of CVL average power, a high frequency of excitation pulse repetition rate is required.

Second, it determines the presence of critical pre-pulse population of metastable states, at reaching which the inversion in the active medium is not realized. This determines the limiting pulse repetition rate (PRR).[5] Consequently, the PRR and the generation average power should be determined by the relaxation process of metastable states in the inter-pulse period.[6]

However, it is well known that metastable states are efficiently destructed through collisions with cooling electrons.[7] This fact allowed us to make an assumption[8] and then prove it experimentally,[9] that metastable states in the active medium can be destructed for period <1 μs and the main limiting factor for PRR is a high pre-pulse concentration of electrons n_e. These electrons can not be heated because of the presence of induction in the laser discharge circuit. There exists a critical pre-pulse concentration of ~ 10^{14} cm^{-3}, at which electrons can not be heated to the temperature, at which the rate of population of the upper laser level exceeds the rate of population of the lower level.[10]

The above-said demonstrates the ambiguity in estimation of frequency and energy characteristics of most well studied CVLs, indicating the necessity of further investigation of RM-lasers in order to determine their potential. The research conducted in Refs. 11–14 has shown that strontium-vapor laser energy characteristics are comparable with those of CVL. The processes proceeding in the active medium of strontium-vapor lasers differ from the same processes in CVL. This fact requires more thorough studies.

In this paper we present the results of experimental studies of self-terminating He–Sr$^+$ laser (1.03 and 1.09 μm) frequency and energy characteristics by the method of additional pulse injection before each excitation pulse, as well as the results of numerical modeling of kinetics of the processes in active medium corresponding to experimental conditions.

The experiments were conducted with the gas-discharge tube (GDT), the discharge channel of which was a BeO-ceramic tube with a 15 mm inner diameter and a 500 mm length. The electrodes were located at the ends of the discharge channel in cold buffer zone of GDT. As the buffer gas, helium at a pressure of ~13.2 kPa was used. The pulse-periodic mode of the double-pulse excitation of the active medium was realized at the sacrifice of the storage capacitor discharge by thyratrons: of the excitation pulse – by the TGI1-500/20 thyratron and of the additional pulse – by the TGI1-270/12 thyratron.

The energy of excitation and additional pulses was changed by varying the voltage at the high-voltage rectifiers. In each channel, initial voltages at storage capacitors were twice higher than the voltages at rectifiers due to the use of resonant charge scheme. Excitation pulse repetition rate varied in the range 15–19 kHz. Current and generation pulses were recorded with the help of current shunt

0235-6880/08/08 598-04 $02.00

and PEC-24 coaxial detectors, respectively. The recorded signals were sent to Tektronix TDS-3032 oscillograph. The generation average power was controlled by the power meter OPHIR (Nova-II). The SZS-20 optical filter, transmitting a ~1 μm radiation, and the SZS-8 optical filter transmitting a 3 μm radiation were used to study the generation spectral composition.

At the initial stage of the experiment, with the help of the excitation pulse the strontium-vapor laser has reached the working mode of simultaneous generation at the following wavelengths λ: 6.45; 2.60; 2.69; 2.92; 3.01; and 3.06 μm SrI, as well as 1.03 and 1.09 μm SrII with a total oscillation power of ~800 mW. Then an additional pulse with an adjustable delay relative to the excitation pulse[15] was applied to GDT. Voltage of the high-voltage rectifier varied during the experiment between 0 and 3.6 kV, as well as the capacity of the secondary channel storage capacitor (500, 891, and 1650 pF). The voltage of the high-voltage rectifier (3.6 kV), capacitance of the storage capacitor (891 pF) in the channel of excitation pulse formation, as well as the capacitance of sharpening capacitor (94 pF) did not change.

The experiments conducted revealed that the decrease of the delay between the excitation and the additional pulses (at comparable pumping energies in the both pulses) does not change the generation energy at self-terminating transitions both of SrI atom and SrII ion in the additional pulse. However, the decrease of the generation energy at SrI self-terminating transitions in the excitation pulse was observed. At the same time, in a certain delay range an increase of the generation pulse energy at the SrII self-terminating transitions in the excitation pulse took place. Oscillograms of current and generation pulses at self-terminating IR-transitions of SrII (λ = 1.03 and 1.09 μm) in additional and excitation pump pulses at 0.72 and 2.6 ms delay, respectively, are presented in Figs. 1 and 2.

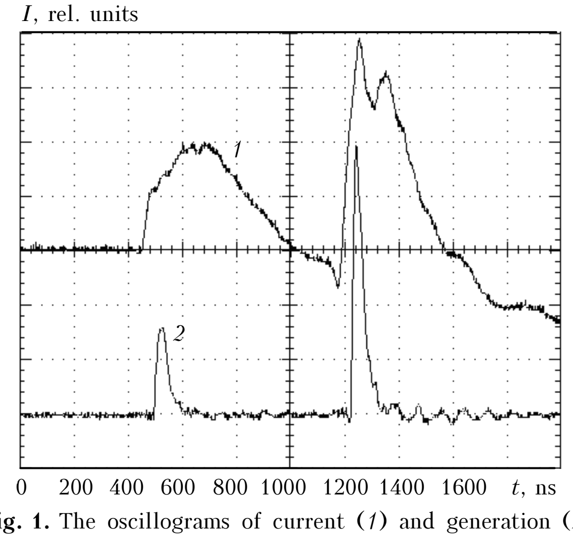

Fig. 1. The oscillograms of current (*1*) and generation (*2*) pulses at SrII IR-transitions at 0.72 μs delay between additional and excitation pulses.

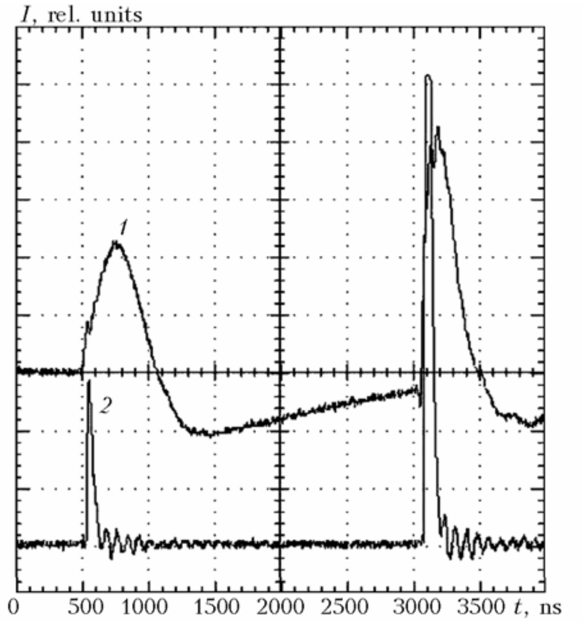

Fig. 2. The oscillograms of current (*1*) and generation (*2*) pulses at SrII IR-transitions at 2.6 μs delay between additional and excitation pulses.

Numerical modeling of kinetics of the processes in the active medium can give us a deeper insight into them. The modeling was done using a self-consistent model of the He–Sr$^+$ laser.[16] The mathematical model includes the consistent description of electric circuit and pulse-periodic discharge plasma. Modeling of the electric circuit is reduced to the differential equations for currents and voltages, which are solved jointly with kinetic equations for plasma parameters. When calculating level-by-level strontium ion kinetics, 20 excited levels, shown in Fig. 3, were taken into account.

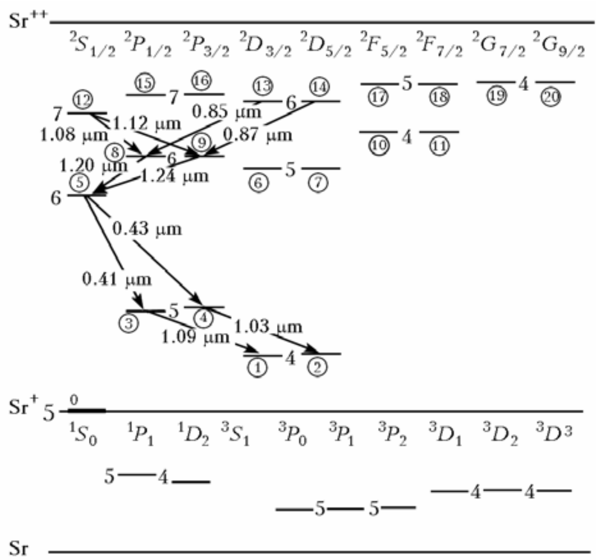

Fig. 3. The scheme of levels of strontium atom and ion (the arrows indicate SrII transitions, at which laser generation is observed, the numbering of SrII levels used in mathematical model is shown in circles).

Figure 3 also illustrates the numbering of levels used in the calculations.

Differential equations for the population balance of SrII excited levels is of the form:

$$\frac{dN_i}{dt} = \sum_{\substack{j=0 \\ j\neq i}}^{20} (A_{j,i} + F_{j,i} + G_{j,i}) N_j - \sum_{\substack{k=0 \\ k\neq i}}^{20} (A_{j,k} + F_{j,k} + G_{j,k}) N_i - \\ - \sum_{i=1}^{20} K_{\mathrm{Sr}^{+*}_{(i)}} N_{\mathrm{Sr}^{+*}_{(i)}} N_e + \delta_i + W_p^{(i)}; \ i = 1...20,$$

where $A_{i,k}$ are probabilities of optical transitions; $F_{i,k} = <\sigma_{i,k} v_e> n_e = V_{i,k} n_e$ are probabilities of electron excitation or deexcitation; $G_{i,k} = K_{i,k} N_{\mathrm{He}}$ are probabilities of atom excitation or deexcitation; $K_{\mathrm{Sr}^{+*}_{(i)}}$ are constants of ionization rate of excited states; δ_i are terms accounting for the effect of saturation at laser transitions; $W_p^{(i)}$ are partial rates of pumping levels.

The parameters, approximately corresponding to experimental conditions, were used in the modeling. When calculating double-pulse modes, equal capacitance of storage capacitors (C = 1000 pF) and initial voltages for both pulses were used.

Figures 4–6 illustrate the results of modeling of the double-pulse mode at a 2.6 μs interval between the pulses and initial voltage U = 7.25 kV at storage capacitors (discharge current I, unsaturated amplification coefficient κ at SrII IR-transitions, reduced populations of working levels N1–N4 and plasma parameters: concentration n_e and electron temperature T_e).

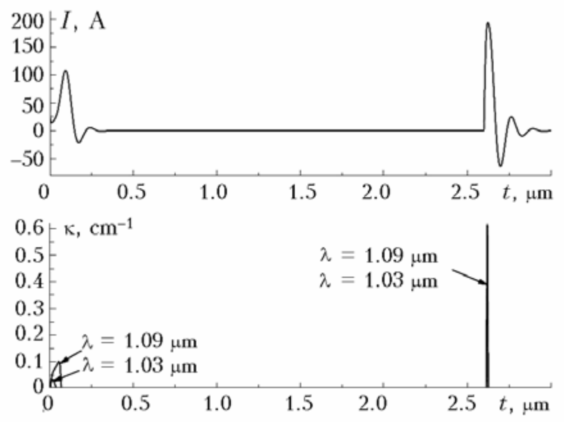

Fig. 4. The calculated additional and excitation current pulses and amplification coefficients at SrII IR-transitions at a 2.6 μs delay.

As is seen in Fig. 5, efficient electron deexcitation of SrII metastable states at < 1 μs interval occurs in the inter-pulse period, that determines the limiting pulse repetition rate equal to ~ 1 MHz.

The increase of amplitude and shortening of the second current pulse (as compared to the first one) was observed in the double-pulse mode both in the experiment (Fig. 2) and in modeling (Fig. 4). This is due to high residual pre-pulse electron concentration n_e (Fig. 5) and, correspondingly, high pre-pulse plasma conductivity.

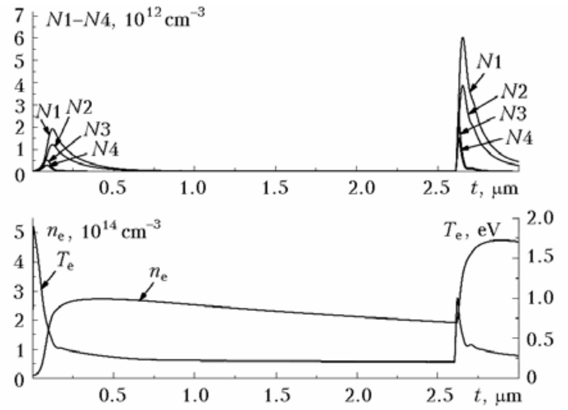

Fig. 5. The calculated populations of working levels (λ = 1.03 μm: N4 → N2; λ = 1.09 μm: N3 → N1), concentration n_e and electron temperature T_e.

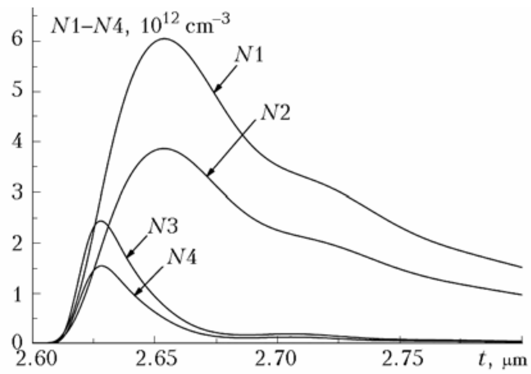

Fig. 6. The calculated populations of working levels (λ = 1.03 μm: N4 → N2; λ = 1.09 μm: N3 → N1) in the second excitation pulse.

Amplification is higher in the second pulse (Fig. 4) and even higher than in single-pulse mode. This agrees with the experimental data (Fig. 2) and follows from the fact that at a short pulse interval, a significant concentration of strontium ions exists, which has not time for recombination to the beginning of the second pulse. These ions mainly determine the pre-pulse concentration n_e (Fig. 5). Consequently, the share of energy, consumed for Sr^+ ions generation from the ground state of Sr atoms, decreases and the share of energy consumed for SrII resonance level excitation from Sr^+ ground state increases. Notwithstanding the fact that the increased pre-pulse concentration n_e prevents rapid electron gas heating and leads to the decrease of T_e in the second current pulse, the populations of resonance levels and the inversion increase (Figs. 5 and 6).

Thus, the conducted experiments and modeling of kinetics of the processes in the self-terminating He–Sr^+ laser active medium have shown that generation pulse repetition rate can reach ~1 MHz due to quite a fast relaxation of strontium ion metastable states caused by the electron deexcitation.

The increase of the generation pulse energy in the excitation pulse in some range of delays between additional and excitation pulses is revealed, which is caused by a significant residual pre-pulse concentration of strontium ions, having not enough time for recombination.

References

1. A.N. Soldatov and V.I. Solomonov, *Gas-discharge Lasers on Self-terminating Transitions in Metal Vapors* (Nauka, Novosibirsk, 1985), 151 pp.
2. V.M. Batenin, V.V. Buchanov, M.A. Kazaryan, I.I. Klimovskii, and E.I. Molodykh, *Lasers on Self-terminating Transitions of Metal Atoms* (Scientific Book Pub., Moscow, 1998), 544 pp.
3. C.E. Little, *Physics, Engineering and Applications* (John Wikey & Sons, New York, 1999), 620 pp.
4. N.A. Yudin, V.M. Klimkin, and V.E. Prokop'ev, Quant. Electron. **29**, No. 9, 828–831 (1999).
5. M.A. Kazaryan, N.A. Lyabin, and N.A. Yudin, J. of Russian laser Research. **25**, No. 3, 267–297 (2004).
6. A.A. Isaev, G.G. Petrash, and I.V. Ponomarev, Sov. J. Quant. Electron. **16**, No. 11, 1512–1516 (1986).
7. B.M. Smirnov, *Excited Atoms* (Energoizdat, Moscow, 1982), 231 pp.
8. P.A. Bokhan, V.I. Silant'ev, and V.I. Solomonov, Sov. J. Quant. Electron. **10**, No. 6, 724–726 (1980).
9. P.A. Bokhan and D.E. Zakrevskii, Quant. Electron. **32**, No. 7, 602–608 (2002).
10. S.I. Yakovlenko, Quant. Electron. **30**, No. 6, 501–505 (2000).
11. A.N. Soldatov, A.G. Filonov, A.S. Shumeiko, A.E. Kirilov, B. Ivanov, R. Haglund, M. Mendenhall, B. Gabella, and I. Kostadinov, Proc. SPIE **5483**, 252–261 (2004).
12. T.M. Gorbunova, A.N. Soldatov, and A.G. Filonov, Atmos. Oceanic Opt. **17**, Nos. 2–3, 231–234 (2004).
13. A.N. Soldatov, A.G. Filonov, and A.V. Vasil'eva, Atmos. Oceanic Opt. **19**, Nos. 2–3, 201–203 (2006).
14. A.N. Soldatov, A.G. Filonov, Yu.P. Polunin, and I.V. Sidorov, in: *Proc. of the 8-th Sino-Russian Symp. on Laser Physics and Laser Technologies*, Tomsk, 2006, pp. 26–29.
15. A.N. Soldatov, Atmos. Oceanic Opt. **6**, No. 6, 383–387 (1993).
16. G.D. Chebotarev, O.O. Prutsakov, and E.L. Latush, Proc. SPIE **5483**, 83–88 (2004).