

## Gas discharge lasers with pulse repetition frequency up to 100 kHz on RM transitions in alkali earth metal ions

*M.A. Lavrukhin<sup>1,\*</sup>, P.A. Bokhan<sup>1</sup>, P.P. Gugin<sup>1</sup>, I.M. Ananyev<sup>2</sup>, D.E. Zakrevsky<sup>1,2</sup>*

<sup>1</sup>*A.V. Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk, Russia*

<sup>2</sup>*Novosibirsk State Technical University, Novosibirsk, Russia*

*\*lavrukhin@isp.nsc.ru*

**Abstract.** We present the results of experimental studies of the output parameters of the lasers with a volume of 0.1 dm<sup>3</sup> at RM transitions in barium and calcium ions. For Ca<sup>+</sup> laser an average power of 4.5 W at a pulse repetition frequency of 100 kHz was achieved in the burst operation mode. For Ba<sup>+</sup> laser the obtained steady-state average output power in the burst-mode operation amounted to 74 mW at a pulse repetition frequency 40 kHz. Typical laser pulse duration at half-maximum equaled correspondingly 13 and 5 ns for Ca<sup>+</sup> and Ba<sup>+</sup> lasers.

**Keywords:** metal vapor lasers, eptron, calcium, barium.

### 1. Introduction

Pulsed gas discharge lasers on resonance-metastable (RM) transitions still remains in-demand devices due to their unique parameters, which include high gain coefficient, narrow line-width, large radiation pulse power, etc. [1]. Specific areas of their application include active optical systems, dermatology, micromachining and etc. In general lasers on RM atom transitions are more efficient and powerful than on the ion ones. However, this situation can be different in case of high pulse repetition frequency (PRF), because maximum of the average output power  $P_{av}$  for atom RM transitions is reached at lower values of PRF. For example, for the copper vapor laser maximum of the average output power lies in the range of ~10–30 kHz [1]. High PRF is important in active optical systems, because it determines temporal resolution. So, it is valuable to study other ion RM lasers operating at high PRF (100 kHz and more), as they may be more suitable for this distinct application. Also, a lot of ion RM transitions in UV spectrum range exists [2], which increases potential interest in the investigation of these lasers. Excitation of RM lasers at high PRF is complicated due to high prepulse electron concentration, which requires rapid voltage growth between the GDT electrodes in order to achieve preferable electron temperature for laser levels excitation. To mitigate this problem appropriate nanosecond switching devices, such as described in [3, 4], can be applied.

The highest average power and efficiency for ion RM lasers was achieved for Ca<sup>+</sup> laser at 854.2 and 866.2 nm [5]. In a GDT with a length of 15.2 cm and a bore of 4 cm the maximum average power was 0.74 W at  $f = 6.85$  kHz and the maximum efficiency  $\eta = 0.05\%$  [6].

### 2. Experimental setup

Laser gas discharge tube (GDT) was manufactured from BeO ceramics with inner diameter of 1.5 mm and length of 55 cm (Fig.1). The operating temperature of the active medium was maintained by an external heater. The studies were carried out using helium as a buffer gas in the active medium of the laser. Two different active medium were investigated. Firstly, lasing on the  $6p^2P^{\circ}_{3/2} - 5d^2D_{5/2}$  ( $\lambda = 614.2$  nm) RM transition in Ba<sup>+</sup> was studied. Then, after evaporating in vacuum barium from the GDT volume, calcium metal pieces were placed into the GDT. In this case, lasing occurred on the  $4p^2P^{\circ}_{3/2} - 3d^2D_{5/2}$  ( $\lambda = 854.2$  nm) and  $4p^2P^{\circ}_{1/2} - 3d^2D_{3/2}$  ( $\lambda = 866.2$  nm) Ca<sup>+</sup> RM-transitions.

The studies were carried out using excitation circuit which consisted from a parallel assembly of IGBTs and a pulse transformer with a conversion ratio of 1:30. An uncontrolled gas-discharge switch based on a capillary discharge with a plasma cathode (eptron) was used to rapidly increase the voltage across the GDT (Fig.2.). Helium at a pressure of 4–10 Torr was used as the operating

gas in the switch, the voltage rise times on the switch and GDT were 0.2–0.5  $\mu\text{s}$  and 2–3 ns correspondingly.

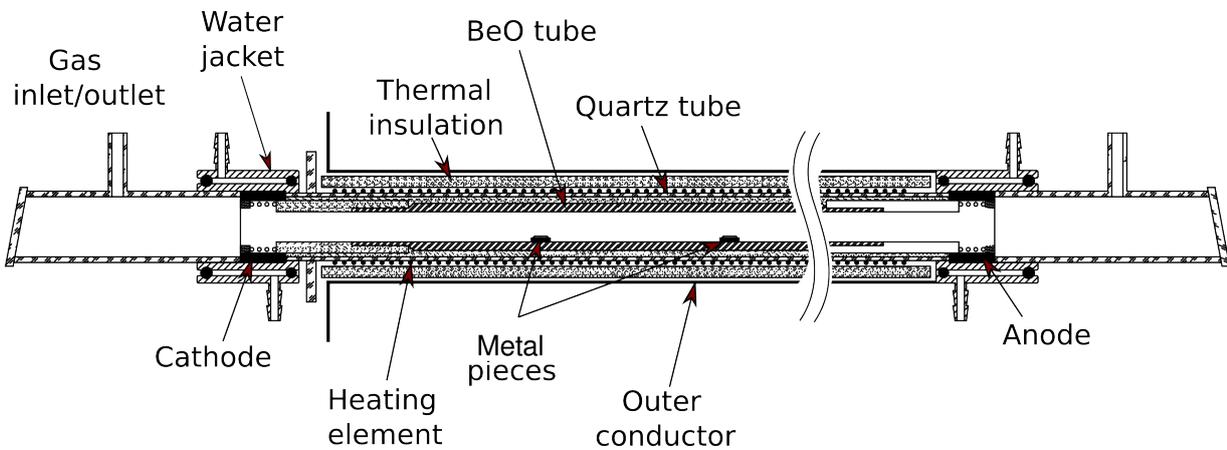


Fig.1. Gas discharge tube scheme.

The laser operated in the burst mode, which allowed to carry out measurements with independent control of the pumping power and temperature of the GDT wall  $T$ . The repetition frequency of the bursts was 0.5 Hz, the number of pulses in the burst amounted 150. Thus, the power input from the generator into the discharge did not exceed 2% of the power from the resistive heater and almost did not affect the temperature of the GDT wall. The temperature measurements were carried out immediately after switching off the excitation pulses.

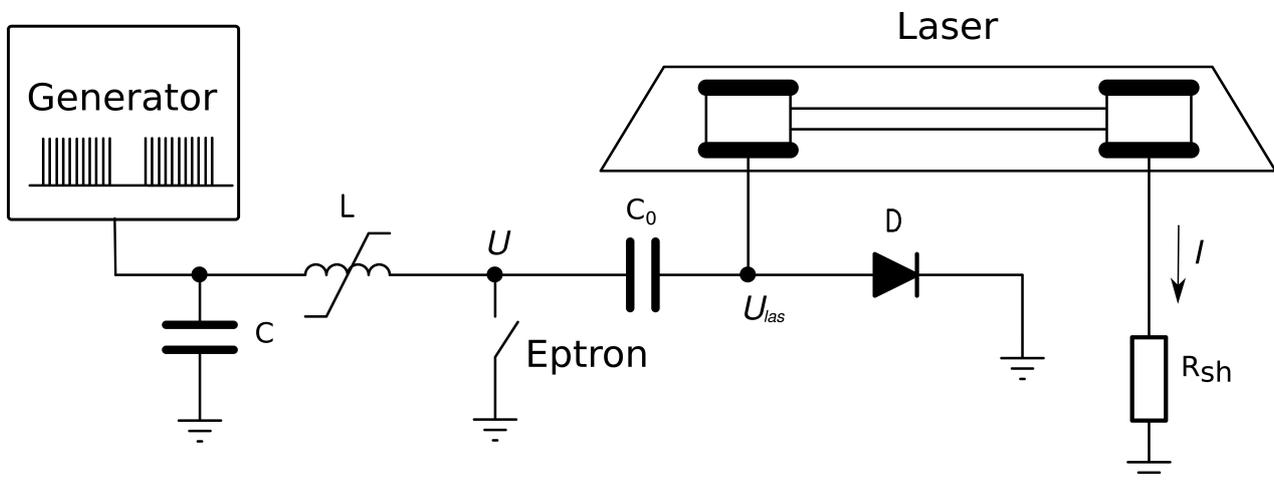


Fig.2. Laser excitation circuit.

The current through the GDT was measured using a low-inductance shunt  $R_{sh}$  from chip resistors. Resistive voltage dividers were used to measure the voltage across the GDT and the eptron. The measurement of the voltage amplitude  $U_a$  was carried out on the capacitance  $C_0$ . All waveforms were observed on a Tektronix MDO3104 oscilloscope (1-GHz bandwidth).

A dielectric spherical mirror (5 m in diameter) with  $R > 99.5\%$  and a flat quartz plate ( $R = 8\%$ ) were used as a resonator. The output windows were similar quartz plates without anti-reflection coating. Registration of the radiation was performed using a vacuum photodiode FK-32 with time resolution better than 1 ns, which was calibrated by thermal power sensor Thorlabs S401C.

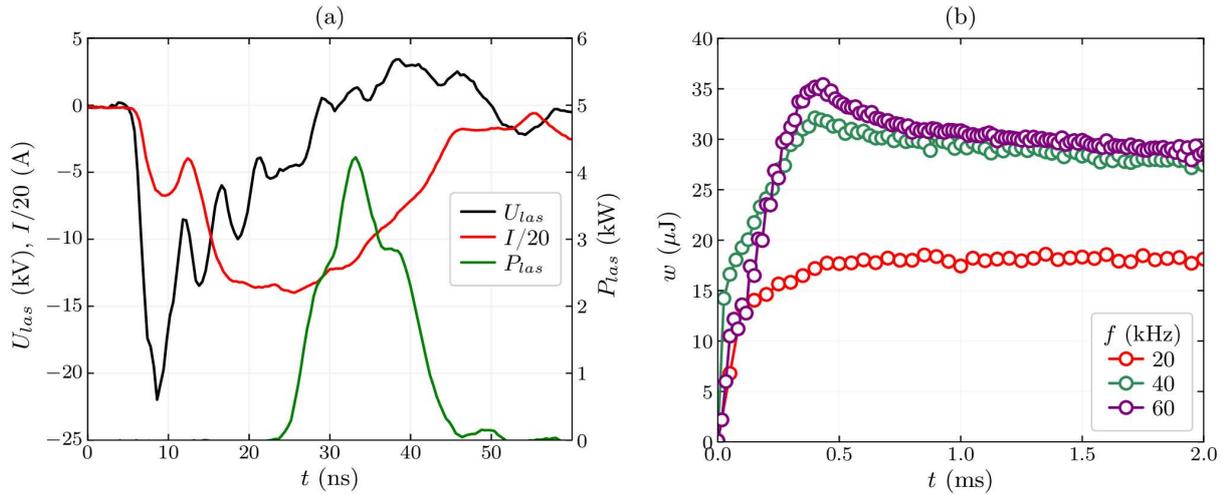


Fig.3. Voltage  $U$ , current  $I$  and laser power  $P_{las}$  waveforms (a) and laser pulse energy  $w$  evolution during the burst (b) for RM  $\text{Ca}^+$  laser. (a) –  $T = 700$  °C,  $C_0 = 330$  pF,  $U_a = 22.5$  kV,  $p_{He} = 10$  Torr,  $f = 50$  kHz; (b) –  $T = 680$  °C,  $C = 500$  pF,  $U_a = 17.5$  kV,  $p_{He} = 10$  Torr, each point indicates a single laser pulse.

### 3. Results and discussion

The studies were carried out in the burst operation mode, the evolution of the laser pulses as the pulse number in the burst increases is shown in Fig.3b. The shape of oscillograms of current through GDT and voltage on GDT stabilizes during first 5–10 pulses of the burst, while the evolution of laser pulses continues up to significantly higher pulse numbers. After some time after the beginning of the burst the energy of laser pulses stops changing and enters the steady-state mode (Fig.3b), for which all further measurements of laser radiation parameters were carried out. The characteristic duration of the laser pulse in the steady-state mode was 13 ns at half-maximum for  $\text{Ca}^+$  RM laser and 5 ns in case of  $\text{Ba}^+$ .

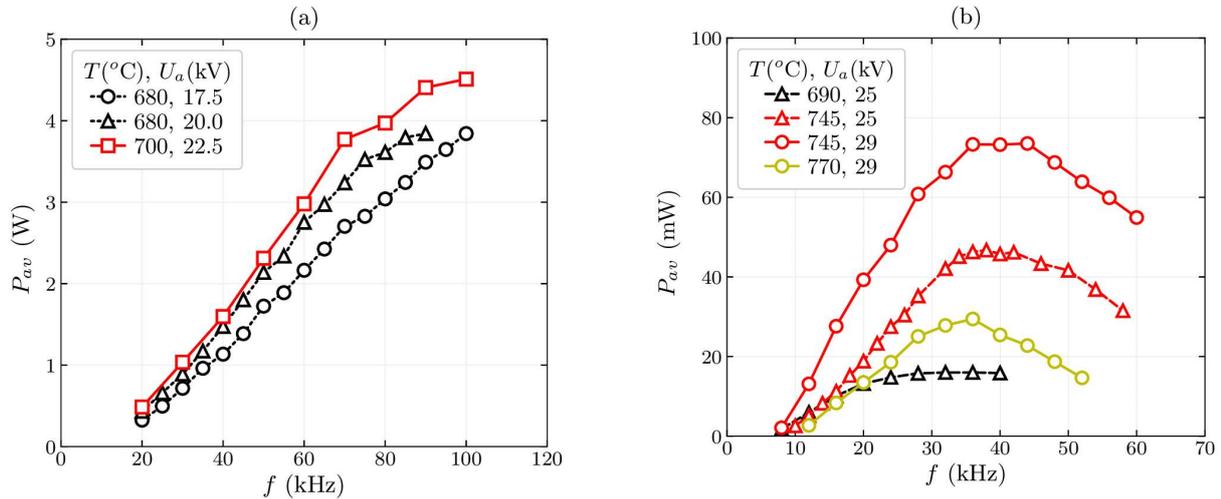


Fig.4. Average output power in the steady-state mode versus pulse repetition frequency  $f$  for  $\text{Ca}^+$  (a) and  $\text{Ba}^+$  (b) RM lasers. (a) –  $p_{He} = 10$  Torr,  $C_0 = 330$  pF; (b) –  $p_{He} = 20$  Torr,  $C_0 = 165$  pF.

The maximum energy stored in the working capacitance  $C_0$  for the applied generator was 0.16 J. Under these conditions, the maximum efficiency and average power is reached at the GDT wall temperature 700 °C, which corresponds to a calcium vapor pressure of 0.11 Torr [7]. An increase in GDT wall temperature leads to an increase in the pumping energy at which the

maximum efficiency is reached. At further heating of GDT up to  $T = 715$  °C the pumping generator energy becomes insufficient to reach the maximum of  $\eta(U_a)$  dependence even at  $U_a = 26$  kV. The highest obtained value of the average laser power  $P_{av}$  was 4.5 W (Fig.4a) and the pumping power  $f \cdot C \cdot U_a^2 / 2$  at the end of the burst, including losses in the switch, reached 8.4 kW.

For  $Ba^+$  RM laser it can be seen that the highest value of  $P_{av}$  is reached at  $T = 745$ °C (Fig.4b). At PRF  $f = 40$  kHz  $P_{av} = 74$  mW was obtained. For a larger values of  $T$  the pumping pulse energy is not sufficient to increase  $P_{av}$ .

#### 4. Conclusion

The results show the advantage of using a high-voltage nanosecond switch with a high pulse repetition frequency based on capillary discharge with plasma cathode (eptron) for improving RM ion lasers output parameters. It is demonstrated that optimal pulse repetition frequency, at which average output power reaches maximum value, for  $Ca^+$  RM laser exceeds 100 kHz. That is several times higher than in case of neutral atom RM lasers (copper, gold, etc.) [1].

For  $Ca^+$  laser total average output power of 4.5 W at a pulse repetition frequency of 100 kHz was achieved in the burst operation mode, which exceeds previous results [5] for almost an order of magnitude. For  $Ba^+$  RM laser obtained at 40 kHz average output power reached 74 mW.

Presented results are of high interest since they can be applied for other more practically valuable RM ion lasers. Especially UV lasers, for instance,  $Hg^+$  ( $\lambda = 398.4$  nm) [8] and  $Cu^+$  ( $\lambda = 201.5$  and 211.2 nm) [9] RM lasers.

#### Acknowledgements

This work was financially supported by the Russian Science Foundation (project No. 19-19-00069).

#### 5. References

- [1] Little C.E., *Metal vapour lasers: physics, engineering and applications*. (New York: Wiley-VCH, 1999).
- [2] Markova S.V., Petrash G.G., *Proc. SPIE*, 166, 1993; doi: 10.1117/12.160511
- [3] Bokhan P.A., Gugin P.P., Zakrevsky D.E., Lavrukhin M.A., *Russ. Phys. J.*, **62**(11), 2059, 2020; doi: 10.1088/1361-6595/ab9d91
- [4] Bokhan P.A., Belskaya E.V., Gugin P.P., Lavrukhin M.A., Zakrevsky D.E., Schweigert I.V., *Plasma Sources Sci. Technol.*, **29**, 84001; doi: 10.1088/1361-6595/ab9d91
- [5] Karras T., *Lasers '81: Proc. of the International Conference*, New Orleans, USA, 871, 1982.
- [6] Ivanov I.G., Latush E.L., Sem M.F., *Metal Vapour Ion Lasers*. (New York City: John Wiley & Sons, 1996).
- [7] Yaws C., *The Yaws Handbook of Vapor Pressure: Antoine coefficients*. (Kidlington: Gulf Professional Publishing, 2015).
- [8] Markova S.V., Petrash G.G. *Quantum Electron.*, **25** (9), 841, 1995; doi: 10.1070/qe1995v025n09abeh000483
- [9] Carman R.J., *Opt. Lett.*, **21**(12), 872; doi: 10.1364/ol.21.000872