CADMIUM-VAPOR AND STRONTIUM-VAPOR CATAPHORETIC PULSED LASERS

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In this paper we present, for the first time, theoretical grounds for the cataphoretic injection of metal vapor into the laser active media that was experimentally performed in the pulse-periodic He−Cd+ *and* He−Sr+-*lasers. In a small-size* He−Sr+-*laser with a* 3-mm-*diameter and* 26-cm-*long discharge channel we have achieved a high, for the cataphoretic pump-through of metal vapor, mean power of lasing* (510 mW) *and record values of the specific mean power* (277 mW/cm^3) *and gain coefficient* (0.15 cm^{-1}).

1. The cataphoresis phenomenon in cw metal-vapor lasers has presently been well studied and widely used.[1–3] The main advantages of using cataphoresis for injecting vapor into the discharge channel are the possibility of achieving uniform distribution of the active metal atoms along the discharge channel, the absence of screening of the lasing channel cross section by pieces of a solid metal, no necessity to use the external heater to produce metal vapor, and the possibility of creating necessary density of metal vapor independent (in certain limits) of the discharge current.

It is just the cataphoretic cw cadmium-vapor laser (λ = 441.6, 354, and 325 nm) that is most widely, among the metal vapor lasers, used in various applications and has the highest sale's volume.[3,4]

As to the pulsed metal-vapor lasers (MVL) the cataphoresis, in application to injecting the metal vapor into the discharge in this case, has not been even analyzed so far, to say nothing of its use in practice. Rather it was attempted to avoid this effect since it made the active medium inhomogeneous. This was done by uniformly distributing pieces of a metal along the discharge channel.[3] It is also characteristic of pulsed MVLs that self-heating by the discharge current[3,5] is normally used for creating vapor in the active lasing zone.

In the meantime, from the most general considerations, no any restrictions exist on applying the cataphoresis for making the injection of the vapor into the discharge uniform and convenient. Moreover, this may be performed with making use of all the above-mentioned advantages characteristic of cw lasing mode. Besides, one may also try to add the advantages of the pulsed mode of MVL operation. The first one is that in the pulse mode one always have a larger number of wavelengths at which the lasing may occur. Thus, for instance, in cadmium vapor the pulsed lasing occurs at 26 wavelengths in the region from 0.325 to 3.288 μm.[3] For the second, the list of active media that provide for lasing in the pulsed mode, which sometimes, as in the so-called self-limited and recombination lasers, is the only possible mode in principle, is much more extended. For the third it is just the pulsed mode that provides from achieving the highest peak and mean powers of lasing in the MVL.

As far as it is concerned the laser applications the pulse-periodic lasing mode could also be preferred in many practical cases (microtechnologies, medicine, and others) or the availability of many wavelengths comes to the first place (color treating in medicine, fluorescence spectral analysis, holography, and multi-color laser projectors), if the pulse mode itself is not critically important.

In this paper we analyze the feasibility and prospects of the cataphoretic injection of metal vapor into the active zone of a pulse-periodic electric discharge. In addition, we discuss the possibilities of using this effect for creating homogeneous active media in the charge exchange He−Cd+ and in He−Sr+ recombination lasers that are essentially different in the pump mechanisms and lasing properties.

2. Let us now estimate the rate of a metal vapor pump through that may be achieved in a discharge tube in a pulse-periodic mode of operation. The velocity of ordered motion of a metal ion, as a function of time, during an electric discharge in a gas may be written[3] as follows:

$$V_i = V_0 \left[1 - \exp\left(- t/\tau\right)\right], \tag{1}$$

where $V_0 = bE_i$ is the steady state velocity of the metal ion; b is the ion mobility in the gas discharge; E_i is the electric field strength during the discharge current pulse; $\tau = 1/(\nu_b + \nu_m)$ is the characteristic time during which the steady state velocity of the ordered motion of a metal ion is established; ν_b and ν_m are the frequencies of metal ion collisions with the buffer gas atoms and metal atoms, respectively.

The estimates that we have made based on data from Refs. 6 and 7 for typical conditions of the pulsed MVLs operation show that $\tau \approx$ 0.1 to 1 ns and this time

is much shorter than typical duration ($\tau_i \sim 0.1$ to 1 μs) of the discharge current pulses. As a consequence, one may present, with a high degree of accuracy, the velocity V_i by the following expression:

$$V_i = V_0 = bE_i. \tag{2}$$

Normally, to excite a pulsed electric discharge in a gas, the circuits are used with a complete discharge of a storage capacitor. In that case the value E_i as function of time t may be written as follows:

$$E_i = E_0 \exp(-t/\tau_i), \tag{3}$$

where E_0 is the initial strength of the electric field in a pulsed discharge. By substituting expression (3) into (2) one finds that the mean, over the pulse duration, velocity of ions is

$$<V_i> = \frac{1}{\tau_i} \int_0^\infty V_i(t)\, \mathrm{d}t = bE_0. \tag{4}$$

In a pulse-periodic mode of laser operation the mean velocity of ordered motion of ions is

$$V_f = <V_i> \tau_i (1/T) = bE_0 \tau_i f, \tag{5}$$

where T is the period and f is the pulse repetition frequency.

Then, for the mean rate of metal vapor pump through the active volume in a pulse-periodic discharge we obtain the following expression:

$$V = bE_0 \tau_i f \theta, \tag{6}$$

where $\theta = n^+/n$ is the coefficient of the metal vapor ionization; n^+ and n are the concentrations of metal ions and atoms averaged over the discharge tube radius.

Typical parameters of the discharge used to provide for excitation of the medium in He−Cd$^+$ laser are $E_0 \approx 100$ V/cm, $\tau_i \sim 0.2$ μs, and $f \sim 5$ to 10 kHz.[3] Using these values and the data from Ref. 8 for b and θ ($b \approx 0.357$ m$^2 \cdot$V$^{-1} \cdot$s^{-1}, at the helium pressure $p_{He} \approx 3$ Torr; $\theta \sim 10^{-1}$) one obtains from equation (6) that the pump-through velocity of cadmium vapor is $V_{Cd} \approx 35$ to 70 cm/s. Similar estimates made for a He−Sr$^+$ laser ($E_0 \approx 1000$ V/cm; $\tau_i \sim 0.1$ μs; $f \sim 5$ to 10 kHz[3]; $b \approx 7.1 \cdot 10^{-3}$ m$^2 \cdot$V$^{-1} \cdot$s^{-1}, at the helium pressure $p_{He} \approx 0.5$ atm; $\theta \sim 0.5$, see Ref. 9) give for the mean velocity of the strontium vapor pump through the active volume to be $V_{Sr} \approx 20$ to 40 cm/s. Thus, it is seen that the values of the cataphoretic pump-through rates for cadmium and strontium vapor in a pulsed discharge are comparable with those in cw metal-vapor lasers. So, we have shown that in principle the cataphoretic injection of metal vapor into the active media of pulse-periodic MVLs could certainly be useful. However one should keep in mind that along

with a high pump-through rate of metal vapor needed for creating an active medium by use of cataphoresis, one also must achieve a uniform distribution of the vapor along the discharge channel. The condition that should hold for the vapor distribution to be uniform along the discharge channel, in the case of cataphoretic pump-through of the vapor, may be derived from the equation of diffusion for metal vapor. In Ref. 1 one may find a derivation of this equation for the case of a continuous discharge

$$\frac{\partial^2 n}{\partial z^2} + \frac{\beta}{L}\left(\frac{\partial n}{\partial z}\right) = 0, \tag{7}$$

where

$$\beta = \theta\, e\, E_0\, L/(k\,T). \tag{8}$$

Here e is the electron charge, k is the Boltzmann constant, L is the length of the channel active part, z is the coordinate along the discharge tube axis, and T is the gas temperature. To apply equation (7) to the description of the diffusion in the case of a steady state pulse-periodic mode, when n is independent of time t, one may average the electric field strength over large enough number of pulses. In that case the parameter β entering equation (7) takes the form

$$\beta = [\theta\, e\, E_0\, L/(k\,T)]\, \tau_i\, f, \tag{9}$$

and a solution to equation (7) will describe the distribution of metal vapor in the pulse-periodic discharge, i.e.,

$$n/n_0 = 1 - \exp[\beta(1 - z/L)]/(1 - \exp\beta), \tag{10}$$

where n_0 is the number concentration of metal vapor coming from a vaporizer.

This solution is valid for the boundary conditions that at $z = 0$, $n = n_0$, that means that at the vaporizer the vapor concentration is constant, while at $z = L$ (the position of a vapor condenser) it vanishes, $n = 0$. In figure 1 set out is the ratio n/n_0 as a function of the parameter β. It is seen from this figure that at

$$\beta \geq 10, \tag{11}$$

one can obtain more or less uniform distribution of vapor along the discharge channel while locking the vapor from the anode side. Thus, the condition (11) becomes a criterion of the vapor distribution uniformity along the discharge channel. From the expression (9) one readily may see that typical conditions for operation of pulse-periodic He−Cd$^+$ and He−Sr$^+$ lasers well satisfy the criterion (11) since it gives $\beta_{Cd} = 10-20$ (for $L = 50$ cm, $T = 600$ K) and $\beta_{Sr} = 95-190$ (for $L = 26$ cm, $T = 870$ K).
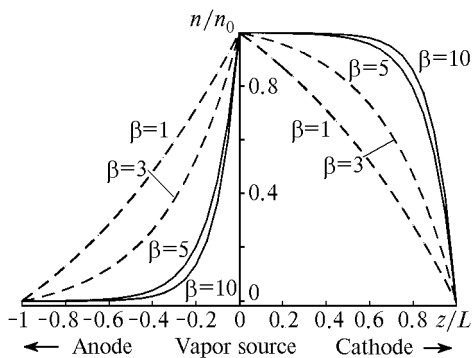
FIG. 1. The distribution of metal vapor (relative concentration) along the discharge tube in a cataphoretic MVL. The value $z/L = 0$ corresponds to the position of a metal vapor source.

3. In the experiments with a He−Cd⁺ laser we have used a typical gas-discharge tube, depicted in Fig. 2, that is normally used in cw cataphoretic He−Cd⁺ lasers. The active discharge length in that laser was 50 cm and the capillary channel had the diameter of 3 mm. The vaporizer container was loaded with a piece of metal cadmium that was heated with an external oven. The pulse generator used for the electric discharge pump is constructed based on the circuitry with a complete discharge of a storage capacitor through a thyratron at a pulse repetition frequency of 5 to 10 kHz. The pressure of helium in the discharge tube varied from 2 to 5 Torr.
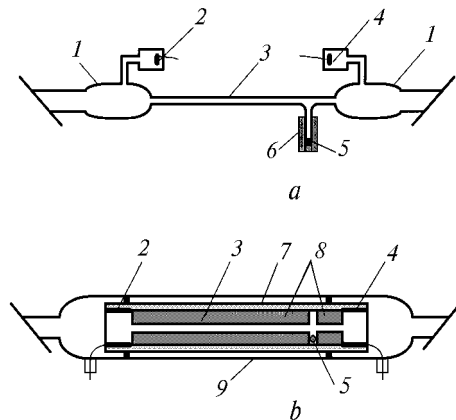

FIG. 2. Discharge tubes of pulsed cataphoretic He−Cd⁺ (a) and He−Sr⁺ (b) lasers, where 1 is a condenser; 2 is the cathode; 3 is the active zone (L = 50 cm, d = 3 mm in a He−Cd⁺ laser, L = 26 cm, d = 3 mm in a He−Sr⁺ laser); 4 is the anode; 5 is the vaporized metal; 6 is a heater; 7 is the outer tube from BeO (35-cm-long and 13 mm in diameter); 8 is the inner tube from BeO; 9 is the glass housing.

The process of cataphoretic pump through of metal vapor along the discharge tube could be observed by visually tracking the color boundary dividing the discharge. As observed the pump-through velocity was 5 to 10 cm/s that agrees with the calculated value. In this pulsed He−Cd⁺ laser with the cataphoretic

injection of metal vapor into the discharge we have obtained, for the first time, laser emission at the CdII lines with the wavelengths 533.7 and 537.8 nm. The oscillographic traces of the spontaneous emission and of the laser one are shown in Fig. 3a. The gain coefficient, as estimated by the technique of calibrated losses, was found to be $\chi = 30\%$ m⁻¹, the mean power of the laser emission being 2 mW.
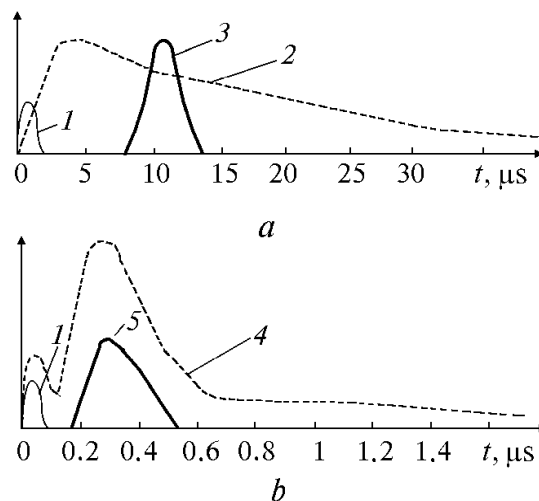

FIG. 3. Oscilloscope traces of the spontaneous emission and of the laser emissions at CdII (a) and SrII (b) lines; 1 is the discharge current pulse; curves 2 and 3 are the pulses due to spontaneous and laser emission at $\lambda = 533.7$ and 537.8 nm of CdII; curves 4 and 5 are the pulses due to spontaneous and laser emission at $\lambda = 430.5$ nm of SrII.

We did not manage to obtain simultaneous lasing at the blue ($\lambda = 441.6$ nm) and the pair of green lines ($\lambda = 533.7$ and 537.8 nm) in our cataphoretic He−Cd⁺ pulse-periodic laser, since much lower pulse current is needed for achieving the lasing at the blue line.[3] However, in a combined cw-pulsed mode of the discharge pumping we have overcome this difficulty in a He−Cd⁺ laser by optimizing the pulse current for lasing at green lines while selecting the continuous current optimal for a cw lasing. In that mode of operation the lasing ability of the active medium at $\lambda = 441.6$ nm restores in 500 µs interval after the electric-current pulse termination. At the same time the continuous electric current caused a three-time decrease in the lasing amplitude at the green lines. This happens due to weakening of the electron deactivation.[3] For this reason it is hardly an optimal mode of the laser operation to provide for simultaneous lasing at these three wavelengths.

One may try to achieve this task more effectively by commutating the electric current pulses of relevant amplitudes. If no necessity exists to provide for three-line lasing one should optimize the operation mode for each line separately by forming the pulses of corresponding shape and amplitude. Moreover, if the

mean discharge current happens to be insufficient for self-heating of the active discharge zone one may apply an additional thermal insulation of the discharge tube.

For making experiments with a He−Sr⁺ laser we have built up special cataphoretic discharge tube with the inner diameter of 3 mm and 26-cm-long active zone (see Fig. 2*b*). In these experiments we used a power supply constructed based on Blumlein[10] circuit. The vaporization of strontium took place in a separate cavity in a self-heating mode of the laser operation. In that case the main discharge channel was strongly overheated what hampered the metal vapor condensation on its walls. In these experiments we have managed to obtain for the first time, for the cataphoretic pump through of strontium vapor in pulse-periodic mode, lasing at the wavelength of 430.5 nm. In this experimental laser we have obtained lasing at the pulse repetition frequency f = 25 to 50 kHz that is quite high for that type of lasers. The pressure of helium in these experiments varied from 0.3 to 1 atm. The oscillographic traces of the spontaneous emission and of the laser one at 430.5 nm wavelength are shown in Fig. 3*b*. The optimal He pressure was p_{He}=0.7 to 0.8 atm. The mean power of the laser emission reached 510 mW what makes, at the active volume of 1.84 cm³, the specific mean power to be p_m^{sp} = 277 mW/cm³, the latter value being a record for He−Sr⁺ lasers. This value is 3.8 times higher than that achieved earlier in a self-heating He−Sr⁺ laser with no forced cooling (73 mW/cm³)[11] and 2.1 times higher than that in a laser with circulating water cooling (130 mW/cm³).[12] The gain coefficient, as estimated by the technique of calibrated losses, was also found to be maximum for the He−Sr⁺ laser (χ = 0.15 cm⁻¹).

Such high specific energy characteristics of the output emission have been achieved owing both to the cataphoretic injection of the metal vapor and other design features of the discharge tube. Use of cataphoresis provides for obtaining a uniform vapor distribution along the active part of the discharge channel. In that case the metal itself is placed outside the discharge channel thus casting no any shadow on the cross section of a narrow lasing channel. Besides, no spontaneous sparking or arcing occurs in the discharge channel on metal pieces that otherwise can cause uncontrolled vaporization of the metal. In this particular laser we used a thick-wall ceramic tube for the gas discharge volume.

As it follows from Ref. 12 the optimal pulse repetition frequency in the self-heating lasers is determined by the heat transfer rate that, in its turn, is proportional to the outer diameter of the ceramic tube. Therefore, when increasing the outer diameter of the tube while keeping the inner one constant we may improve the heat transfer, thus creating better conditions for increasing the pulse repetition frequency and, as a consequence, of the mean output power of the laser.

Thus, in this paper we have given, for the first time, theoretical grounds for and presented experimental results on injecting metal vapor into the active media of pulse-periodic He−Cd⁺ and He−Sr⁺ lasers using cataphoresis. In a small-size He−Sr⁺ laser with the discharge channel of 3 mm in diameter and 26 cm long we have achieved, at the cataphoretic pump through of Sr vapor, quite high mean power (P_m = 510 mW), a record specific mean power (P_m^{sp} = 277 mW/cm³) of the output emission, and a record value of the gain coefficient (χ = 0.15 cm⁻¹).

This technology of introducing vapor of a lasing substance may be useful in other pulsed lasers that uses vapor of chemical elements and substances as, for instance, CuBr, Ba, Ca, etc.

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