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CAPACITIVELY COUPLED RADIO-FREQUENCY EXCITED INFRARED He-Cd LASER

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Abstract. Laser oscillation on near-infrared cadmium ion transitions was obtained in a transverse radio- frequency excited He-Cd discharge. Lasing on two of them: 853.0 nm and 887.8 nm was reported for the first time as laser oscillation excited by a radio-frequency discharge. The optimum conditions at cw and pulsed mode of operation were determined yielding a maximum small signal gain coefficient of 24 %/m for the 806 nm laser.

The similarity between radio-frequency excited and hollow cathode discharges was proved by the infrared Cd^+ lines behaviour on discharge conditions.

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1. Introduction

The transverse capacitively coupled radio-frequency (RF) discharge was successfully employed for excitation of many gas laser systems. Laser action on a considerable number of ionic transitions of different metals and inert gases such as Ti, Cd, Zn, Hg, Se, Cu, Ar, Kr was realized [1-3]. Oscillation on all these transitions was previously obtained in a hollow-cathode (HC) discharge. In the negative glow of the HC discharge a group of high energy electrons exists providing good conditions for laser lines excitation. A similar mechanism of producing high energy electrons exists in the transverse RF discharge, in which at certain conditions a high electric field is formed near the electrodes [4, 5]. The correspondence between the two types of discharges was proved by the comparable laser output powers obtained in a hollow cathode and capacitively coupled RF excited discharges at nearly the same discharge conditions [6]. Besides, the capacitively coupled RF discharge possesses some advantages over the HC discharge because of its better longitudinal homogeneity, the absence of arcing, and much simpler laser tube design.

One of the most promising as a practical RF excited laser is the capacitively coupled RF excited He-Cd$^+$ laser, capable of oscillating simultaneously on many lines in the whole visible spectrum. Recently, owing to a new discharge tube technology, a cw capacitively coupled RF excited white-light He-Cd$^+$ laser was developed exhibiting a reliable operation for more than 400 hours and delivering stable, tens-milliwatt power at the three primary spectral lines: blue ($\lambda = 441.6$ nm), green ($\lambda = 533.7$ nm and $\lambda = 537.8$ m), and red ($\lambda = 635.5$ nm and $\lambda = 636.0$ nm) [7].

Here we report simultaneous laser oscillation on five near-IR Cd ion lines: 723.7 nm, 728.4 nm, 806.7 nm, 853.0 nm, 887.8 nm in a He-Cd mixture using CCRF discharge excitation. To our knowledge generation on the 853.0 nm and 887.8 nm transitions was obtained for the first time in a RF excited discharge. The experiment comprised investigations of the laser oscillation characteristics at pulsed and cw modes of operation, at 27.12 MHz and 13.56 MHz excitation frequencies. The influence of the excitation pulse parameters on the laser parameters was examined. The small-signal gains of the laser lines were measured at pulsed and cw excitation.

2. Experiment

The laser tube (Fig. 1) had a design described in details elsewhere [7]. The laser tube envelope was made of a fused silica. The discharge active zone lengths were 400 mm. The Cd vapour was supplied into the discharge zone from a sidearm reservoir connected to the middle of the discharge tube. In our experiments we used two versions of the tube: (*a*) the discharge channel was formed by a fused silica capillary with $d = 8$ mm inner diameter, and (*b*) a capillary tube made of Al_2O_3 ceramic was

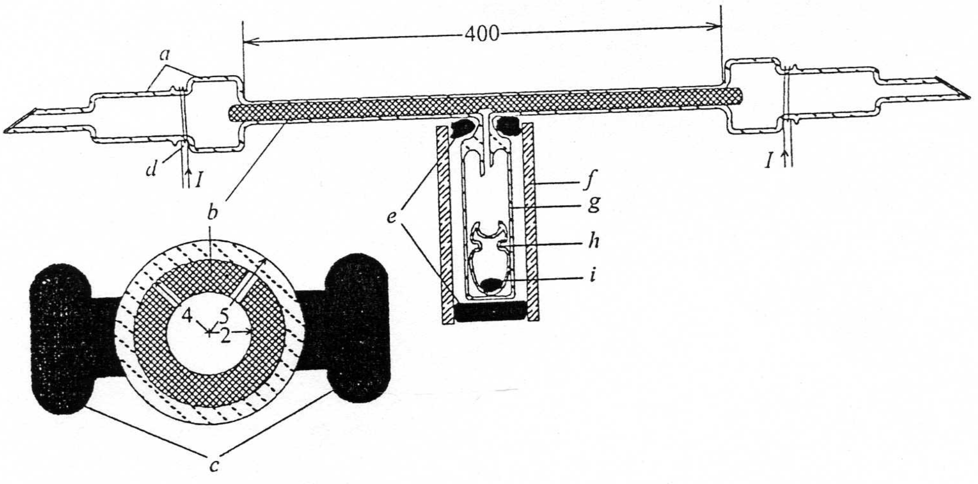

Fig. 1. Laser tube design

(*a*) fused silica tube; (*b*) Al(2)O(3) tube; (*c*) electrodes; (*d*) heater; (*e*) insulating material; (*f*) oven; (*g*) Cd reservoir; (*h*) ampoule; (*i*) Cd inserted into the fused silica tube, reducing the discharge channel to $d = 4$ mm in diameter. The RF power was coupled in the discharge by two 400 mm long external brass electrodes, mounted along the discharge zone. The laser resonator was formed by two pairs of high reflectivity mirrors ($R > 99.5$ %): (A) one for the 710-860 nm spectral band allowing simultaneous oscillation on 723.7 nm, 728.4 nm, 806.7 nm, and 853.0 nm Cd^+ lines, and (B) — for the 800-900 nm spectral band allowing simultaneous oscillation of 806.7 nm, 853.0 nm and 887.8 nm Cd^+ lines.

A schematic diagram of the experimental setup is shown in Fig. 2. Two RF generators were used for discharge excitation, one operating at 27.12 MHz with maximum output power of 2.5 kW, and the other, operating at 13.56 MHz with maximum output power of 700 W. There was a possibility to modulate the RF power in trains of pulses with variable repetition rate from 1 kHz to 4 kHz and pulse duration from 40 μs to 120 μs. Special circuits were developed to match the discharge impedance to the impedance of the RF generators. The matching circuits symmetrized the RF voltage and helped to maintain an uniform discharge between the electrodes and to avoid strong RF interference [7]. The input RF power and the reflected power were measured by a Daiwa RF power meter, connected between the modulator and the matching circuit. The lasers pulses were monitored with a setup: a Bentham grating monochromator, a photomultiplier and a Tektronix TAS475 oscilloscope. The laser gain measurements were made by inserting a calibrated loss element in the laser resonator.

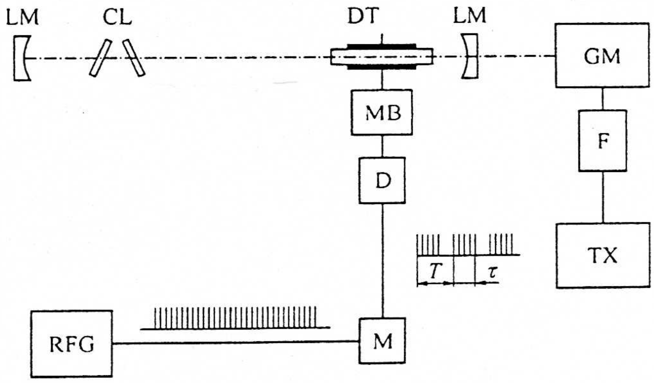

Fig. 2. Experimental setup RFG — radio-frequency generator; M — RF modulator; D — RF power meter; MB — matching circuit; LM — laser mirrors; DT — dischsrge tube; CL — quartz plates for gain measurements; GM — monochromator; F — photomultiplier; TX — oscilloscope

3. Results and Discussion

The oscillation of five near-IR Cd ion lines (Fig. 3): 723.7 nm, 728.4 nm, 806.7 nm, and 853.0 nm and 887.8 nm was obtained at both 27.12 MHz and 13.56 MHz excitation. All these lines were earlier obtained in a $He-Cd^+$ HC discharge [8]. Two of the laser lines: 853.0 and 887.8 nm were, to our knowledge, for the first time observed at RF excitation.

The optimal Cd vapour pressure was obtained at about 570 K reservoir temperature for all He pressure and RF input power, so during all experiments we maintaining the reservoir temperature constant. However, the laser tube wall temperature influenced the uniform Cd vapour distribution along the tube length. The tube was heated by the discharge and its temperature depended directly on the dissipated RF power in the tube. If the power is too high, the tube is overheated and He is displaced from the active zone. At lower RF power the uniformity of the longitudinal Cd vapour distribution was poor. In both cases the redistribution of the active medium resulted in lower laser power.

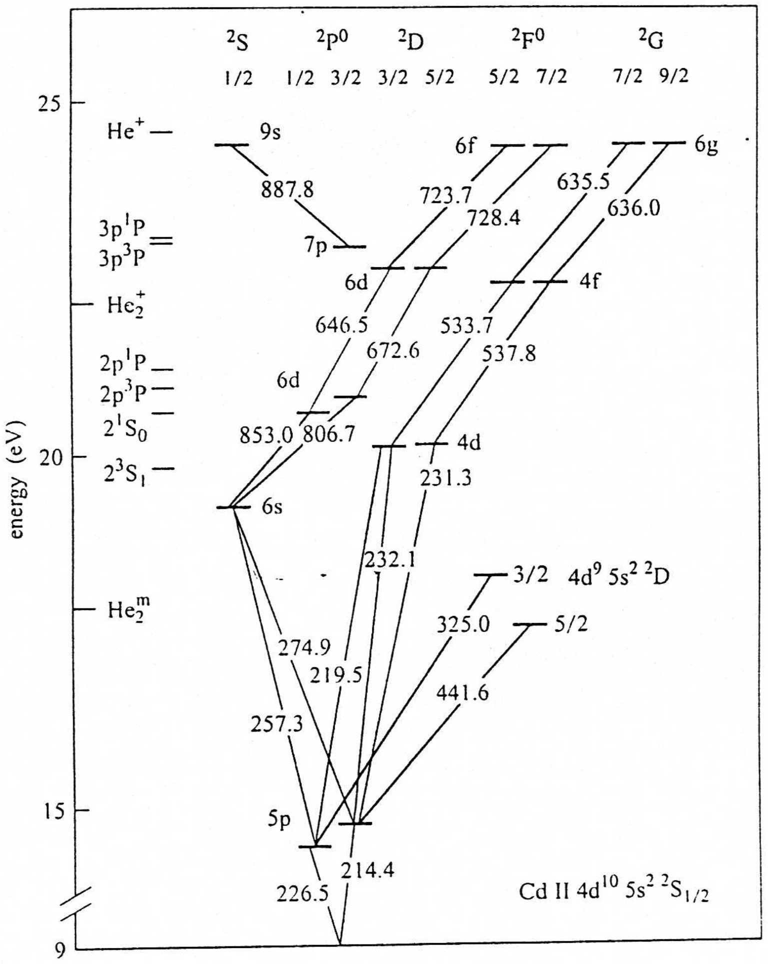

Fig. 3. Partial energy level diagram of Cd II

The optimal RF input power at cw mode of excitation was 330 W for the 8 mm quartz capillary tube and 400 W for the 4 mm ceramic capillary tube.

At pulsed mode of excitation the optimal tube wall temperature was determined by changing the average input power (pulse repetition rate or pulse duration) at constant amplitude of the RF pulses. In Fig. 4 a typical laser output power dependence on the average RF power is shown. For all laser lines the optimal average input power was about 50 W. The existence of the optimum average RF input power could be associated with an optimal value of the gas temperature and is in agreement with the result obtained earlier [9].

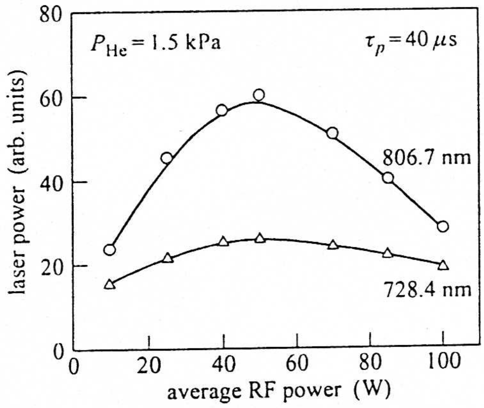

Fig. 4. Laser power dependence on average input power at constant RF pulse power of 620 W

$\tau_p = 40\ \mu s$ and $p_{He} = 1.5$ kPa

A typical time behaviour of excitation and laser pulses is shown in Fig. 5. The laser oscillation started simultaneously with the excitation pulse. The laser power always reached its maximum at the end of the RF pulse for all pulses duration applied — from 40 μs to 120 μs. A long afterglow lasing (up to 600 μs) was observed after the end of the excitation pulse. At optimal pressure and pulse repetition rate higher than 2 kHz the afterglow lasing lasted longer than the interval between the excitation pulses. The laser power did not case before the next RF pulse and the lasing could be considered as quasi-cw.

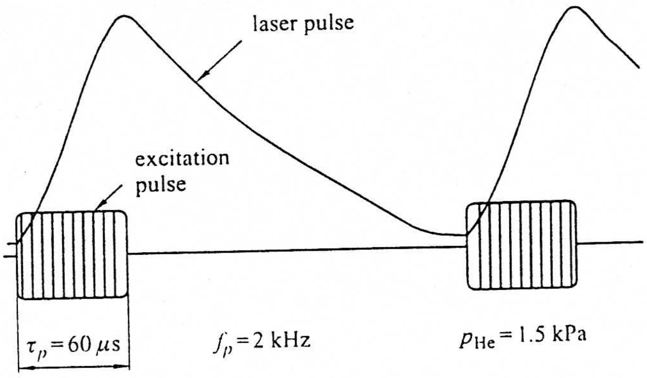

Fig. 5. RF excitation pulse and laser pulse shape

The laser output power dependence of the RF pulse amplitude was measured at optimal average input power 50 W (Fig. 6) by changing the pulse repetition rate at constant pulse duration. As it is seen in Fig. 6, the intensity of the 728.4 nm line increased almost three times when doubling the excitation pulse amplitude, while the intensity of the 806.7 nm line remained practically the same. A similar behaviour of these lines with increasing input power was observed by Fukuda and Miya [8] in a HC discharge. They suggested that such input power dependence was due to the different excitation and deexcitation mechanisms of the laser levels. The upper level of the 728.4 nm transition was excited by a direct charge transfer process between ground state He^+ and Cd atoms. Its lower level was depopulated by the 672.8 nm transition, populating the upper level of the 806.7 nm laser transition (Fig. 3). Besides population of the upper level of the 806.7 nm line by these successive radiative cascade transitions, it is believed that the upper level of the 806.7 nm transition was also populated by direct electron collisions [8]. At high input power when electron density is high, an efficient deexcitation of the 806.7 nm laser levels is also possible [2].

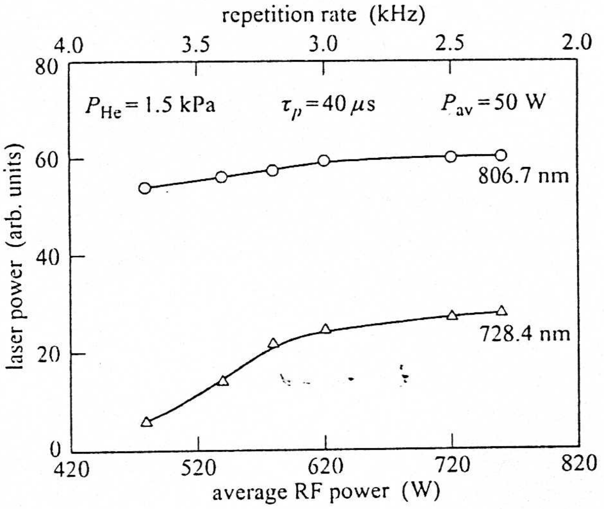

Fig. 6. Laser power dependence on excitation pulse amplitude (or pulse repetition rate) at constant average input power of 50 W
$\tau_p = 40\ \mu s$ and $p_{He} = 1.5$ kPa

The lasing was obtained at a wide range of He pressure: $P_{He} = 0.4$–6 kPa at all excitation conditions: pulsed and cw mode of excitation, at 13.56 MHz and 27.12 MHz, and in both discharge tubes. At lower He pressure the discharge spreads towards the tube windows and discharge instabilities appeared. At higher helium pressure the discharge confined near the tube wall under the electrodes, a dark hole was formed in the center of the discharge, similarly as in the case of the HC discharge at higher pressure [8] as a result the laser output power decreased.

The small-signal gains of all IR lines were measured at optimal excitation conditions for different He pressures. The measured small-signal gains at simultaneous oscillation of the 723.7 nm, 728.4 nm, 806.7 nm and 853.0 nm lines as a function of He pressure at pulsed mode of excitation in the 8 mm quartz tube are presented in Fig. 7. The highest gain was measured on the 806.7 nm transition — more than 18 %/m for the whole pressure band with a maximum of 24 %/m at 2–3 kPa He pressure. Such weak He pressure dependence of the small-signal gain on the 806.7 nm line was in agreement with the result obtained earlier in a HC discharge and attributed to the influence of the electron impact excitation [8]. The highest gains measured on the 728.4 nm and 853.0 nm transitions were 3 %/m and 7 %/m respectively.

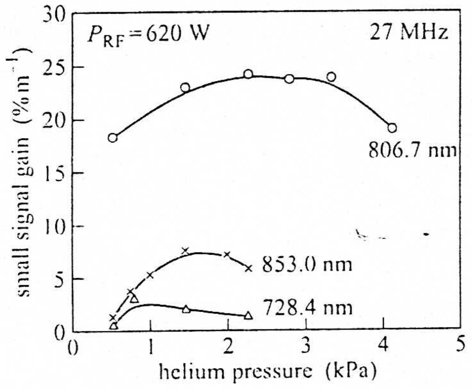

Fig. 7. Small-signal gain as a function of helium pressure in the 8 mm in diameter discharge tube at pulsed mode of excitation: P_{av} = 50 W, f_p = 2 kHz. 27.12 MHz

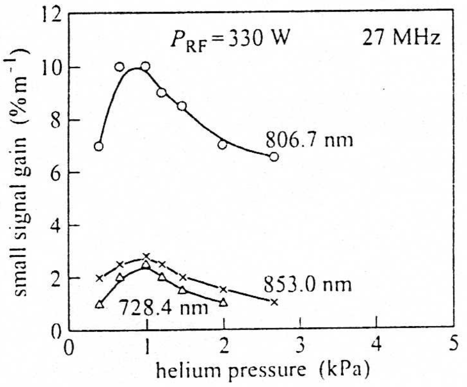

Fig. 8. Small-signal gain as a function of helium pressure in the 8 mm in diameter discharge tube at cw mode of excitation, 27.12 MHz

The small signal gains measured at cw mode of excitation in the same discharge tube were about twice lower than those, measured at pulsed mode of excitation (Fig. 8). The laser lines intensities were more sensitive to He pressure variation. The optimal He pressure was 0.5-1.0 kPa although lasing was observed up to 2.5 kPa He pressure. The measured lower gain could be due to the lower excitation power in the cw mode of operation: 330 W, compared to 620 W at pulsed excitation. Another possible reason for the decrease of laser gain at cw lasing could be due also to the fact that at pulsed mode of operation more favorable plasma conditions for laser excitation were provided [2, 9].

An improvement of the output power and gain of all IR Cd$^+$ laser transition was observed when a ceramic capillary was inserted in the fused silica capillary forming a narrower discharge channel. Due to the reduced diameter of the active zone the optimal He pressure was higher — 2 kPa compared to 1 kPa in the 8 mm diameter tube.

Figure 9 shows the small-signal gains of the 728.4 nm, 806.7 nm and 853.0 nm Cd$^+$ laser lines as a function of He pressure at 27.12 MHz excitation. The measured gain was about twice higher than that achieved in the 8 mm in diameter fused silica tube. A maximum gain of 20 %/m was obtained on the most intensive line 806.7 nm.

All above measurements were made at simultaneous oscillation of the 723.7 nm, 728.4 nm, 806.7 nm and 853.0 nm Cd$^+$ laser transitions with a laser resonator formed by the first pair (A) of laser mirrors. Using the second pair (B) laser mirrors simultaneous oscillation of the 806.7 nm, 853.0 nm and 887.8 nm Cd$^+$ lines was obtained. By inserting a birefringent Lyot filter [10] in the laser resonator a single line operation of each line was also obtained. Figure 10 shows the small-signal gain of these lines measured at the same discharge and excitation conditions as shown in Fig. 9, but at single line operation. The measured maximum gain on the 806.7 nm and 853.0 nm lines was more than twice lower than that measured at simultaneous oscillation at 723.7 nm, 728.4 nm, 806.7 nm and 853.0 nm transitions. Such decrease of laser gain could be a result of interaction between lines, similar to that, demonstrated earlier for the red and green Cd$^+$ transitions at RF excitation [7].

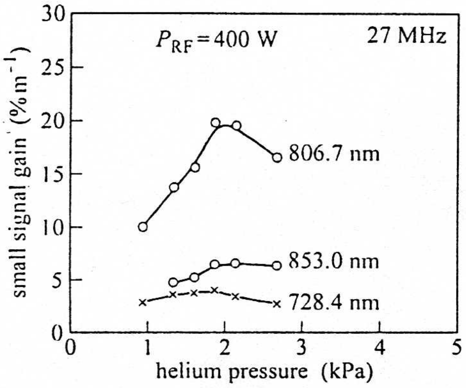

Fig. 9. Small-signal gain as a function of helium pressure in the 4 mm Al_2O_3 discharge channel at cw mode of excitation, 27.12 MHz, at simultaneous oscillation of the 723.7 nm, 728.4 nm, 806.7 nm and 853.0 nm laser lines

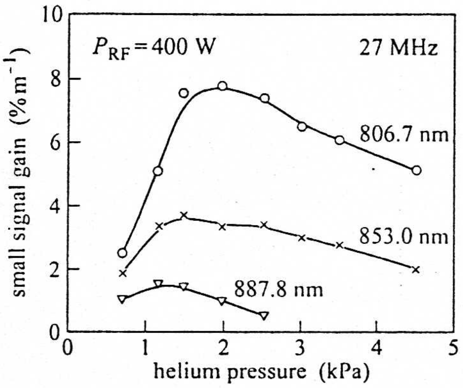

Fig. 10. Small-signal gain as a function of helium pressure in the 4 mm Al_2O_3 discharge channel at cw mode of excitation, 27.12 MHz, at simultaneous oscillation of each 806.7 nm,853.0 nm and 887.8 nm laser lines

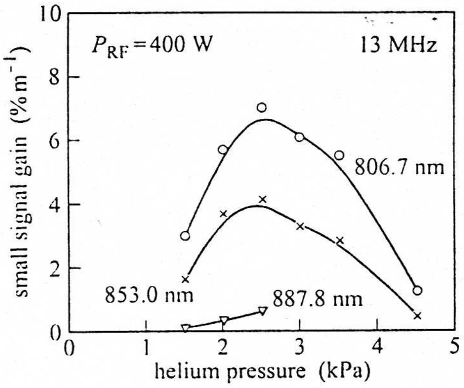

Fig. 11. Small-signal gain as a function of helium pressure in the 4 m Al_2O_3 discharge channel at cw mode of excitation, 27.12 MHz, at single line oscillation

Figure 11 shows the pressure dependence of the small-signal gains of the 806.7 nm, 853.0 nm and 887.8 nm Cd$^+$ transitions at cw excitation with 13.56 MHz and RF input power of 400 W. No essential difference in laser operation was observed when exciting the discharge with 13.56 MHz or 27.12 MHz RF pulses. However, a more homogeneous distribution of the Cd vapour was observed at 27.12 MHz excitation frequency. The He pressure band was a little wider and the laser output power was up to 20 % higher than the power obtained at 13.56 MHz excitation frequency. This observation is consistent with earlier reported results [10] and was probably due to the higher gas temperature achieved at 27.12 MHz excitation.

4. Conclusions

Cw and pulsed oscillation on five near-infrared Cd^+ transitions: 723.7 nm, 728.4 nm, 806.7 nm, 853.0 nm and 887.8 nm, was obtained in a He-Cd^+ RF excited discharge. The lasing on the 853.0 nm and 887.8 nm was reported for the first time as laser oscillation excited by a RF discharge.

The demonstrated earlier [6] similarity between RF excited and HC discharges was proved also by the infrared Cd^+ lines behaviour on discharge conditions.

The small-signal gains of all infrared lines were measured at different modes of operation. A maximum gain of 24 %/m was measured on the 806 nm laser line at pulsed excitation. At cw mode of excitation in the 4 mm Al_2O_3 discharge tube the highest measured gain on the 806 nm transition was 20 %/m.

The spectral range of oscillation of the RF excited He-Cd laser was extended towards the near infrared region. As the optimal discharge conditions for the infrared and visible Cd^+ lines were similar, simultaneous oscillation of all visible and infrared Cd^+ laser lines could be obtained.

Acknowledgment

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