Paper

Radio frequency excited CW gas ion lasers

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ABSTRACT

We report the designs and performances of $He\text{-}Cd^+$, $He\text{-}Kr^+$, $He\text{-}Ar^+$, $He\text{-}Se^+$, $He\text{-}Cu^+(CuBr)$ and $Ne\text{-}Cu^+(CuBr)$ lasers excited with the transverse capacitively coupled radio-frequency discharge. At the similar laser output parameters the designs and operation of the radio-frequency excited lasers are much simpler than those of the hollow-cathode discharge lasers. Under single-line operation the radio-frequency excited $He\text{-}Cd^+$ laser delivered output powers of 60 mW at 441.6 nm, 36 mW at both 533.7 nm and 537.8 nm, and 14 mW at both 635.5 nm and 636.0 nm. The output powers of the $He\text{-}Kr^+$ laser were 22 mW at 469.4 nm, and 11 mW at 431.8 nm. Both lasers exhibited the rms noise-to-signal ratio (0.4-0.6 %) much lower than that of conventional positive column $He\text{-}Cd^+$ lasers. Using a He-CuBr gas mixture laser action on four infrared CuII lines (740.4 nm, 766.5 nm, 780.8 nm and 782.0 nm) was achieved and with a Ne-CuBr gas mixture laser gains on 14 UV-lines between 240.3 nm and 272.2 nm were observed.

INTRODUCTION

Recently the technology of several gas ion lasers has been essentially improved in our laboratories by employing the transverse capacitively coupled radio-frequency (CCRF) discharge for the laser excitation. This concerns such lasers as $He\text{-}Cd^+$, $He\text{-}Kr^+$, $He\text{-}Ar^+$, and $He\text{-}Cu^+(CuBr)$ lasers, successful operation of which was previously proved using the hollow-cathode discharge (HCD). As it was shown by us, operation of the gas ion lasers excited by the transverse CCRF discharge can be realized with the technology much simpler than that of the HCD lasers, at the similar laser output parameters. This make the transverse CCRF discharge attractive for excitation of the gas ion lasers.

Historically, the laser excitation capability of the transverse CCRF discharge has resulted in a considerable number of visible and infrared ionic transitions in Tl, Cd, Zn, Hg, Se, Cu, Kr, and Ar [1-3]. However, technological problems encountered in the CCRF discharges, such as overheating of the discharge tube, deterioration of the inner wall surface of the laser tube by the ion bombardment and introducing of the wall-originated particles into the discharge, have limited the previously carried out investigations mainly to a quasi-CW or pulsed operation regime of the CCRF-excited lasers.

In this contribution results of our effort to develop simple CCRF-excited lasers, exhibiting long-life and stable generation in CW regime are presented.

DESIGNS AND PERFORMANCES OF CCRF-EXCITED $He\text{-}Cd^+$, $He\text{-}Kr^+$, $He\text{-}Ar^+$, $He\text{-}Se^+$, $He\text{-}Cu^+$, AND $Ne\text{-}Cu^+$ LASERS

$He\text{-}Cd^+$ LASER

For practical realization of a long-life CW CCRF-excited $He\text{-}Cd^+$ laser we developed a laser tube, the design of which is shown in Fig. 1. A capillary tube made of Al_2O_3 ceramic (the length - 400 mm, the inner diameter - 4 mm) was inserted into the centrally placed fused silica capillary tube, forming the active part of the laser tube. Using the Al_2O_3 capillary tube allowed to lower the sputter-originated problems, whereby a stable continuous operation of the laser was achieved.

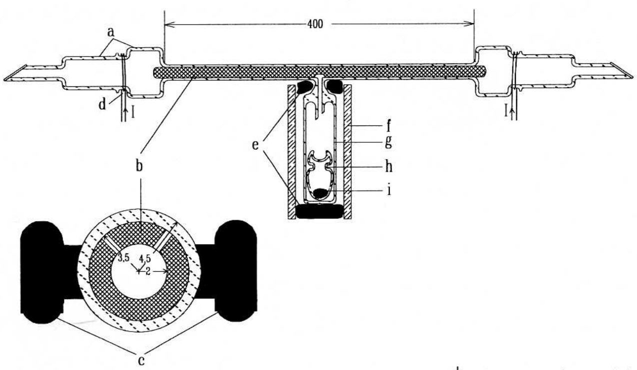

Fig. 1. Design of the CCRF-excited $He\text{-}Cd^+$ laser tube with Al_2O_3 capillary tube insert: a-fused silica tube, b- Al_2O_3 capillary tube, c-RF electrodes, d-heaters, e-insulating material, f-oven , g-Cd reservoir, h-ampoule, i-cadmium.

The RF power was capacitively coupled into the discharge with transverse nickel-plated copper electrodes mounted along the fused silica capillary tube. The discharge was run by a RF generator operating at 13.56 MHz with an output power up to 600 W. A special matching circuit (Fig. 2) was used to transform the laser discharge tube impedance to the 50 Ω output resistance of the RF generator. The matching circuit, consisting of two capacitors and a transformer, symmetrized the RF voltage and was essential to maintain a uniform discharge between the electrodes and to avoid strong RF interference. Both, a nonuniform discharge spreading outside the electrode gap and strong RF interference occurred when a nonsymmetric matching was used. The symmetrizing transformer consisted of two coils, the primary of inductance L_1 = 2.74 μH, and the secondary of inductance L_2 = 11.43 μH. The capacitances could be varied from 45 pF to 650 pF to reach optimum matching. A typical impedance of the laser discharge tube was around $Z_D = (19.5 - j\ 497.3)\ \Omega$ at a RF generator output power of P_g = 400 W and He pressure of 3 kPa. Under these conditions the RF power delivered to the discharge was about 10 % lower than the RF generator output power, and the effective values of the operating voltage and discharge current were 2.14 kV and 4.3 A, respectively. Such a relatively high discharge current is typical for the so-called γ-type of the CCRF discharge [4].

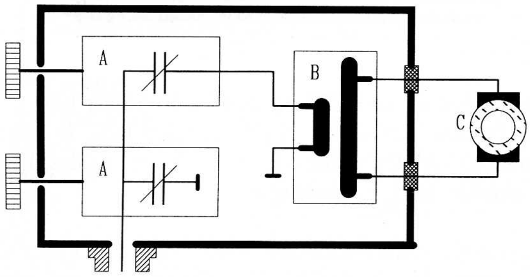

Fig. 2. Electrical circuit supplying RF power to the He-Cd^+ laser tube: A-capacitor (45-650 pF), B-symmetrizing transformer, C-laser tube with electrodes.

The CCRF-excited He-Cd^+ laser exhibited CW single- or multi-line operation at seven wavelengths in blue (λ = 441.6 nm), green (λ = 533.7 nm and λ = 537.8 nm), red (λ = 635.5 nm and λ = 636.0 nm) and infrared (λ = 723.8 nm and λ = 728.4 nm) regions.

At the optimum Cd vapour pressure (80 Pa), He-pressure-dependencies of the CCRF-excited He-Cd^+ laser intra-resonator powers of both red lines, the blue line and the green lines, when oscillating separately are shown in Fig. 3. Similar behaviours were observed for the intra-resonator powers of the HCD He-Cd^+ laser [5].

Laser output powers for separately operating the blue line, both green lines, and both red lines as a function of RF input power are shown in Fig. 4. In Fig. 4, the operating He pressure for each laser line is different and corresponds to the optimum output power of the relevant line (see Fig. 3). As seen from Fig.4, the output powers of all lines increase with increasing RF input power and no saturation is reached up to 400 W. At 400 W, the maximum output powers were about 60 mW, 36 mW, and 14 mW for the blue line, both green lines, and both red lines, respectively. These values are comparable to those obtained in the HCD He-Cd^+ lasers of the same active length [6,7].

Fig. 5 shows the small-signal gains of the He-Cd^+ laser lines as a function of RF input power at the same conditions as in Fig. 4. The small-signal gains of the green and red lines show some saturation with increasing RF power input power at 400 W. At 400 W the small-signal gains were 11 $\%m^{-1}$, 16 $\%m^{-1}$, 13.5 $\%m^{-1}$, and 7$\%m^{-1}$ for the blue line, the green lines λ = 537.8 nm and λ = 533.7 nm, and the stronger red line λ = 633 nm, respectively. These results are similar to those obtained for the HCD He-Cd^+ lasers [5, 8, 9]. The small signal gains for the infrared lines λ = 723.7 nm and λ = 728.4 nm were 1.6 $\%m^{-1}$ and 2.3 $\%m^{-1}$, respectively.

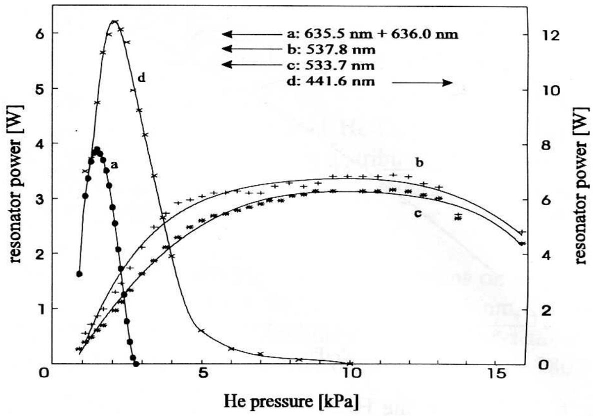

Fig. 3. He-Cd^+ laser intra-resonator power at λ = 441.6 nm, λ = 533.7 nm, λ = 537.8 nm, and λ = 635.5 nm and 636.0 nm as a function of helium pressure. RF input power - 400 W.

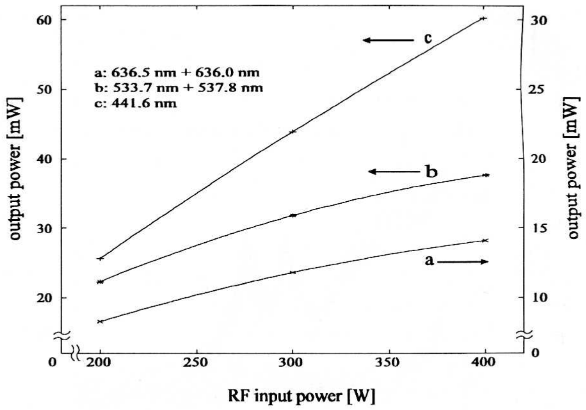

Fig. 4. He-Cd^+ laser output power at λ = 441.6 nm, λ = 533.7 nm and λ = 537.8 nm, and λ = 635.5 nm and λ = 636.0 nm as a function of RF input power.

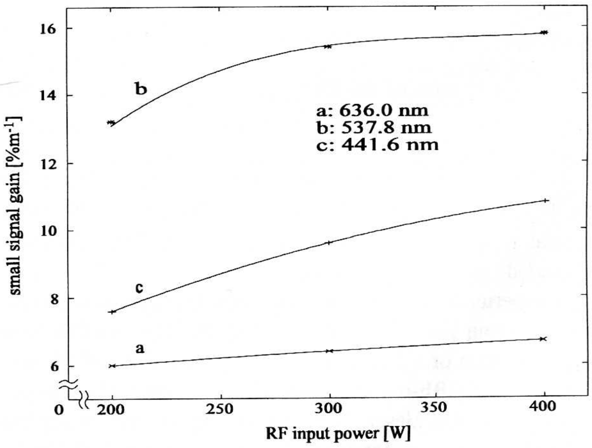

Fig. 5. Coefficients of the small-signal gain for λ = 441.6 nm, λ = 537.8 nm, and λ = 636.0 nm as a function of RF input power.

The experiments on multi-line operation of the CCRF-excited He-Cd^+ laser showed a significant increase in the output power of both red lines and a slight decrease in the output power of the blue line when they oscillated simultaneously with the green lines (Fig. 6). This result is in agreement with that obtained earlier in the HCD He-Cd^+ laser system [5].

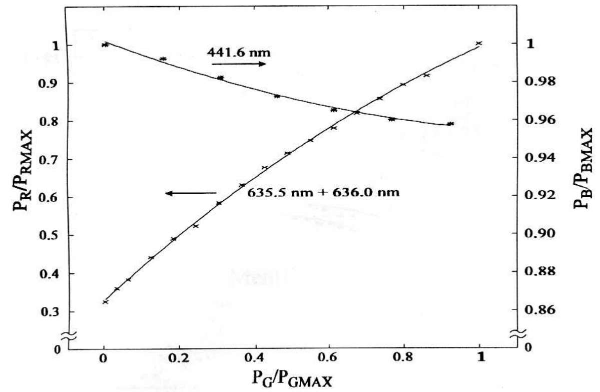

Fig. 6. Influence of the He-Cd$^+$ laser intra-resonator power at $\lambda = 533.7$ nm and 537.8 nm (P_G) upon the He-Cd$^+$ intra-resonator laser output powers at $\lambda = 441.6$ nm (P_B) and $\lambda = 635.5$ nm and 636.0 nm (P_R). P_{Gmax}, P_{Bmax}, and P_{Rmax} are the maximum values of the laser intra-resonator powers of the corresponding lines.

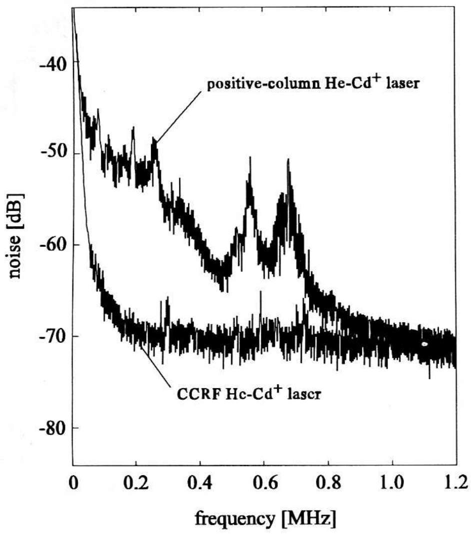

Fig. 7. Noise spectra of the CCRF-excited and positive column He-Cd$^+$ lasers.

The observed increase in the laser output power of the red lines when they operated simultaneously with the green lines can be beneficial if the optimum white-light operation of CCRF-excited He-Cd$^+$ lasers is considered.

The superiority of the CCRF-excited He-Cd$^+$ laser over a positive-column He-Cd$^+$ laser is seen from Fig. 7 which shows the noise spectra of the laser output powers at $\lambda = 441.6$ nm of the presented CCRF-excited He-Cd$^+$ laser and a typical positive-column He-Cd$^+$ laser. The noise-to-signal ratio of the laser output power was less than 0.4 % for the CCRF-excited He-Cd$^+$ laser and about 7 % for the positive-column one.

The investigations of the CCRF-excited He-Cd$^+$ laser have been performed during more than 400 hours. Any essential deterioration of neither the laser tube nor the CCRF discharge have been observed during that period. The above allows inferring that a long-life He-Cd$^+$ laser can be built when the CCRF discharge is used for its excitation.

Additional details can be found elsewhere [10].

He-Kr$^+$ LASER

Laser oscillations on Kr$^+$ ion transitions have been up to now obtained in different CW and pulse HCDs and in the positive column of the pulse glow discharge [3]. Here we report CW laser oscillations on the Kr$^+$ ion transitions at $\lambda = 431.8$ nm, $\lambda = 438.7$ nm, $\lambda = 458.3$ nm, and $\lambda = 469.4$ nm excited with the CCRF discharge in He-Kr mixtures [11].

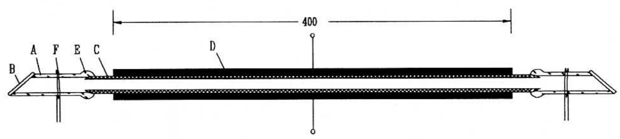

Fig. 8. Design of the CCRF-excited He-Kr$^+$ laser tube with the Al_2O_3 ceramic active part: A - fused silica tube, B - Brewster windows, C - Al_2O_3 ceramic tube, D - RF electrodes, E - fused silica-ceramic joint, F - heating wire.

The He-Kr$^+$ laser oscillations were obtained in a laser tube of a very simple design (Fig. 8). The 400 mm-long active part of the laser tube with an outer and inner diameter of 7 mm and 2.8 mm, respectively, was made of Al_2O_3 ceramic. The ceramic tube ends were connected, using fused silica-ceramic joints, with fused silica end stubs to which fused silica Brewster windows were soldered.

The RF power from the 13.56 MHz generator was capacitively coupled into the discharge with the similar electrodes as in the case of the CCRF-excited He-Cd$^+$ laser.

The matching network (Fig. 2) transformed the laser discharge tube impedance, of about (20 - j 230) Ω at an input power of 600 W, to the 50 Ω output resistance of the RF generator.

At maximum laser output powers for all four lines the He pressure and the He to Kr partial pressure ratio were (13.0 ± 0.3) kPa and 1500 : 1, respectively. The laser oscillation at $\lambda = 469.4$ nm could be achieved in He pressure range from 2.5 kPa to 26 kPa.

The CCRF-excited He-Kr$^+$ laser output powers and small-signal gains at $\lambda = 469.4$ nm and $\lambda = 431.8$ nm as a function of RF input power are shown in Fig. 9. It is seen from it that at a RF input power of 600 W the laser output powers reached 22 mW and 11 mW at $\lambda = 469.4$ nm and $\lambda = 431.8$ nm, respectively. The corresponding values of the small-signal gains were about 7.5 % m^{-1} and 5 % m^{-1}. At 600 W of the RF input power

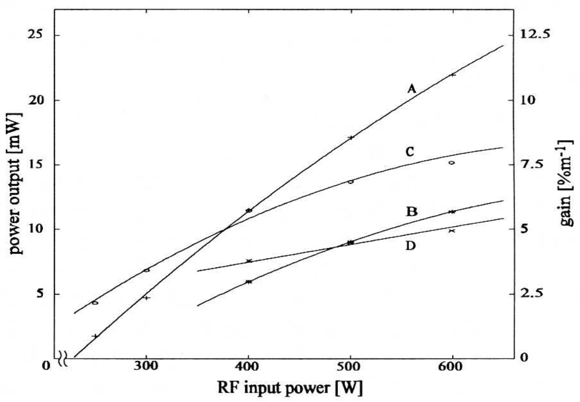

Fig. 9. The CCRF-excited He-Kr$^+$ laser output powers and small-signal gains at $\lambda = 469.4$ nm (A and C) and $\lambda = 431.8$ nm (B and D), respectively.

the laser output power and small-signal gain at λ = 438.7 nm were 1.6 mW and 1.8 % m^{-1}, respectively. The laser oscillation at λ =458.3 nm exceeded barely the threshold (gain was 0.5 % m^{-1} at 600 W). No saturation of the laser output power with increasing RF input power up to 600 W was found.

The rms noise-to-signal ratio of the He-Kr^+ laser output power was lower than 0.6 %, and thus, similar to that of the CCRF-excited He-Cd^+ laser.

The investigations of performance of the CCRF-excited He-Kr^+ laser presented above were carried during about 500 hours. Owing to the Al_2O_3 ceramic discharge tube the laser did not show any essential deterioration after that time.

He-Ar^+ LASER

To our knowledge there has been no report on laser oscillations on ionic transitions of Ar^+ excited in rare gas-Ar mixtures with the CCRF discharges. Using the CCRF discharge we obtained CW laser oscillations on the Ar^+ transitions at λ = 454.5 nm and λ = 476.5 nm in a He-Ar mixture. For this purpose, an Al_2O_3 ceramic discharge tube (40 cm active length, 2.8 mm inner diameter) closed, similarly as in the case of the CCRF-excited He-Cd^+ laser, in a fused silica tube envelope was used. The ratio of the partial pressures of the He:Ar mixture was 100:5. The total pressure of the operating mixture was 4.5 kPa. At 600 W of the RF input power the laser output power at λ = 476.5 nm was 10 mW. However, the operating conditions were not optimized.

He-Se^+ LASER

Using the CCRF discharge for excitation of a He-Se mixture in a laser tube of a similar design to that presented in Fig. 1, we obtained blue-green laser oscillations on 10 of the 62 known ionic laser transitions of Se^+ (12).
The inner diameter of the Al_2O_3 ceramic tube used was 4 mm. The He pressure was varied from 2 kPa to 11 kPa. The Se vapour pressure was 70 Pa. The RF input power was up to 400 W. The CCRF-excited He-Se^+ laser output power was low and unstable, probably due to poor Se vapour distribution along the tube and absorption caused by Se_2 molecules.

He-Cu^+ (CuBr) AND Ne-Cu^+ (CuBr) LASER

Up to now CCRF-excitation of a He-Cu^+ laser was only achieved in a pulsed mode (13) whereby the Cu vapour was produced by sputtering of an internal Cu-electrode. On the other hand CW laser oscillation was demonstrated using a HCD which was seeded with Cu-halides (14). Thus, it was obvious to transfer our technology, developed for a CCRF-excited He-Cd^+ laser, to CCRF excitation of a Cu^+ laser by vaporising CuBr into a CCRF discharge in He or Ne. For realization of this idea a discharge tube similar to that shown in Fig. 1 was used. The CuBr vapour was produced heating the sidearm container filled with CuBr powder up to a temperature of 723 K. To achieve a good CuBr distribution the heated CuBr reservoir is distributed along the discharge tube as shown in Fig. 10. The discharge is operated in an Al_2O_3 ceramic tube of 40 cm length which is enveloped by a fused silica tube. From the sidearm container CuBr vapour diffused to the transverse CCRF discharge region where it was dissociated into Cu and Br atoms. The Cu atoms were ionized and excited by charge transfer reactions with the noble gas ions.

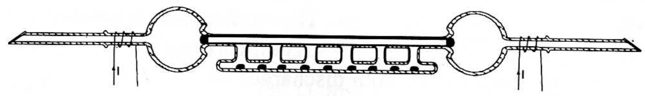

Fig. 10. Tube for CCRF-excited He-Cu^+ laser operated with CuBr. It is vaporized by an oven distributed along the discharge tube into a capillary made of Al_2O_3 ceramic which is inserted into a fused silica tube.

Filling the tube with He the laser oscillations on the Cu^+ ion infrared transitions at λ = 740.5 nm, λ = 766.5 nm, λ = 780.8 nm and λ = 782.6 nm were obtained. Fig.11 shows the output coupling dependency of the laser output power at λ = 780.8 nm for different RF input powers.

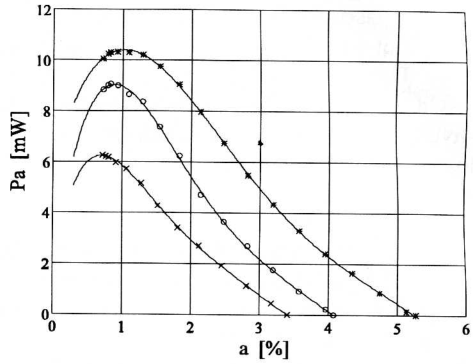

Fig. 11. He-Cu^+ laser output power at λ = 780.8 nm as a function of output coupling for different RF input powers (600 W (×), 700 W (o), 800W (*)), He pressure = 7.2 kPa

At the 780 nm line, which is the strongest line, an output power of 10 mW was achieved at an optimum He pressure of 7 kPa.

Using Ne as a buffer gas the laser gains on the following 14 UV lines were observed: 240.3 nm, 242.4 nm, 247.3 nm, 248.6 nm, 250.6 nm, 252.9 nm, 254.5 nm, 259.1 nm, 260.0 nm, 270.1 nm, 270.3 nm, 271.4 nm, 271.9 nm, 272.2 nm. The strongest line was the 248.6 nm line with an optimum Ne pressure at 1 kPa.

Attempts of achieving UV oscillations on the Cu^+ ion transitions, using Ne-CuBr gas mixture excited in the transverse CCRF discharge are now made.

CONCLUSIONS

In this contribution it was shown that the CCRF discharge is capable of efficient exciting many laser transitions in ions of metals and rare gases. In particular, efficient laser oscillations were obtained in He-Cd and He-Kr mixtures. As it was shown, also laser generations in He-Ar, He-Se, He-CuBr, and Ne-CuBr mixtures are possible with the CCRF excitation.

The CCRF-excited CW multicolour He-Cd^+ laser, oscillating at seven wavelengths in blue, green, red, and infrared regions at tens milliwatts levels, is promising. The He-Cd^+ laser output power in red can be increased by a factor of 3, if all lines operate simultaneously (10). Owing to the power interaction of the green and red lines, the white-light operation of the CCRF-excited He-Cd^+ laser (40 cm active length) with a total output power of about 60 mW is possible.

As far as the laser output power level is concerned the CCRF-excited lasers show no inferiority to the lasers excited by HCDs. However, the output powers comparable to those of the

HCD lasers are obtainable using the CCRF-excited lasers of much simpler laser tube design. The similar laser capabilities of the HCD and CCRF discharges suggest correspondence between the plasma properties of both discharges when optimized for laser operation.

The other advantages of using the CCRF discharge for exciting gas ion lasers, noticed in this experiment, are:

- absence of arcing, which occurs very often in the case of the HCD excitation,
- low degradation of the operating gas by impurity gases owing to the absence of the metal electrodes inside the discharge tube,
- shorter starting time compared to that of HCD lasers,
- relatively low noise of the laser output power.

Owing to the Al_2O_3 capillary tube the CCRF-excited He-Cd^+ and He-Kr^+ lasers exhibited stable operation for more than 400 hours without any essential deterioration of the discharge and laser tube. This allows us to claim that the presented CCRF-excited He-Cd^+ and He-Kr^+ lasers should be useful as a simple, long-lived, continuously operating laser sources operating at tens milliwatts output power levels.

ACKNOWLEDGEMENT

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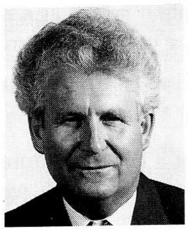

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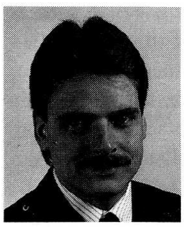

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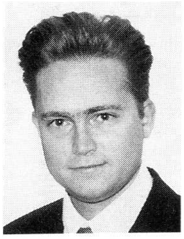

Margarita G. Grozeva (Non-member) She was born in Haskovo, Bulgaria, in 1951. She has graduated Sofia University and received a degree in Physics in 1976 and a degree in Laser Physics and Quantum Electronics in 1978. The Ph. D. degree in Physics she received from the Institute of Solid State Physics, Bulgarian Academy of Sciences, in 1994. Since 1978 she is with the Metal Vapor Lasers Group at the Institute of Solid State Physics, Bulgarian Academy of Sciences, where she is involved in the research and development of gas discharge metal vapor lasers, mainly hollow cathode metal vapor lasers. Her current research interests are concerned with RF-excited gas lasers, particularly sputtering-based metal vapor lasers.

Nikola Vassilev Sabotinov (Non-member) He was born in Bourgas, Bulgaria in 1941. He received the degree in Physics from Sofia University, Sofia, Bulgaria, in 1967, and the Ph. D. degree from the Institute of Solid State Physics, Bulgarian Academy of Sciences, in 1976. His doctoral research concerned He-Cd and He-Se lasers. He received the D. Sc. degree in 1992. He is a Professor and the Head of the Metal Vapor Lasers Group, Institute of Solid State Physics, Bulgarian Academy of Sciences, where he has worked on He-Ne lasers, and since 1970 has been involved mainly in the research and development of metal vapor lasers. Dr. Sabotinov has proposed for the first time the copper bromide laser as a low-temperature alternative of the copper vapor laser. Currently, his research interests include CW positive-column, hollow-cathode and RF excited metal vapor lasers, as well as pulsed metal vapor and metal halide lasers. He has published over 180 papers and over 21 patents in this area.

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