CW Radio-Frequency Excited White-Light He–Cd$^+$ Laser

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***Abstract*— We report on the design and performance of a continuous-wave transverse capacitively coupled radio-frequency excited He–Cd$^+$ laser, which is capable of simultaneously delivering stable, tens-milliwatt power output at the three primary spectral lines blue: (λ = 441.6 nm), green (λ = 533.7 nm and λ = 537.8 nm), and red (λ = 635.5 nm and λ = 636.0 nm). Mixing these lines can result in the laser beam featured by a wide band of colors, including white color. The radio-frequency discharge, that excited the He–Cd mixture inside an alumina ceramic tube (400 mm length and 4 mm inner diameter) inserted into the fused silica tubing, operated between 400 mm long and 4 mm wide outer electrodes. Transformation of the radio-frequency discharge impedance to the 50-Ω output resistance of the radio-frequency generator and symmetrization of the radio-frequency voltage were performed by a special matching circuit. Under single-line operation the He–Cd$^+$ laser output powers of 60 mW, 38 mW and 14 mW were obtained for the blue, green and red lines, respectively, at an input radio-frequency power of 400 W. Owing to the power interaction between the laser oscillations at red and green higher laser output powers in red and green are possible under multi-line operation. At optimum conditions the white-light laser output power of about 60 mW is obtainable from the laser tube of 40 cm active length. The rms noise-to-signal ratio (lower than 0.4%) of the laser output power of the radio-frequency excited He–Cd$^+$ laser was comparable to that of hollow cathode He–Cd$^+$ lasers and much lower than that of conventional positive column He–Cd$^+$ lasers. The presented laser has exhibited stable operation for more than 400 hours, showing ability to become a long life laser.**

I. Introduction

DESPITE of more than thirty-years of intense development of laser technology, a simple, reliable, powerful and cheap laser that simultaneously generates the three primary spectral lines: blue, green and red, a mixture of which can result in a wide band of colors, including white color, is still missing. Such a laser could be used for information processing, including full color printing, film to video conversion and vice versa, film recording and reproduction, image simulation, displays, holographic recording and storage, and optical data storage. Among other possible applications of such a multicolor laser are inspection of surfaces (for example, medical endoscopy and laser color microscopy), inspection of photosensitive materials and multicolor measurements.

One of the most promising candidates for the multicolor laser simultaneously generating the three primary spectral lines has been the hollow-cathode discharge (HCD) He–Cd$^+$ laser [1]. The wavelengths of the HCD He–Cd$^+$ laser oscillations in the blue (441.6 nm), green (533.7 nm and 537.8 nm), and red (635.5 and 636.0 nm) regions are close to those of the ideal three primary spectral lines (450 nm, 540 nm,and 610 nm) [2]. Owing to this the HCD He–Cd$^+$ laser offers a chance for a very wide range of color reproduction. The beam emitted by the well color-balanced HCD He–Cd$^+$ laser appeared white [1], therefore, a HCD He–Cd$^+$ laser emitting such a beam is commonly called a HCD white-light He–Cd$^+$ laser. There have been many studies done on various features of HCD white-light He–Cd$^+$ lasers (see, for example, a short survey in [3]). They proved the high ability of the HCD white-light He–Cd$^+$ laser to reproduce full color pictures [4] using an output power up to 200 mW and a noise-to-signal ratio lower than 1% [5]. These features improve the commercial attractiveness of HCD white-light He–Cd$^+$ lasers. On the other hand, severe technological problems associated with the control of pressure and distribution of Cd vapor in the discharge region, discharge uniformity and stability, gas component separation due to cataphoresis, erosion of the cathode surface due to discharge sputtering, build-up of gaseous impurities, loss of the He buffer gas, and so on, which shorten the lifetime of the HCD white-light He–Cd$^+$ lasers to hundreds of hours, have so far made this laser impractical for commercial applications. The essential development in this field has been recently reported [3].

The high ability of the HCD to generate laser oscillations in He–Cd mixtures, as well as in many other mixtures of the buffer gas (He or Ne) and lasing additive (metal vapor or rare gas, usually much easier ionized than the buffer gas) is a result of two factors. First, a large number of high-energy electrons, needed for excitation of the laser transitions in the lasing additive ions exists in the HCD negative glow, used as an optically active volume [6]. These high-energy electrons are produced by the cathode-emitted electrons accelerating in the electric field of the cathode dark space. Second, in the HCD the number of high energy electrons remains high even if a relatively large fraction of the lasing additive is present [7]. This due to an increase in the operating voltage, caused according to McKeown equation by the increasing number of the low-mobility ions of the additive component. In contrast, in the positive column of the glow discharge, the presence

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of the more easily ionized additive decreases substantially the number of fast electrons. This high fraction of the lasing component in the presence of the large number of high-energy electrons in the laser mixture results in the special excitation capability of the HCD.

The similar mechanism of producing high-energy electrons can exist in the so-called transverse capacitively-coupled radio-frequency (CCRF) discharge, in which a high electric field occurs near the electrodes under certain conditions [8], [9]. This high electric field accelerates the ions toward the electrodes causing emission of electrons, even, if the electrodes are covered with an insulator. This is important for the gas laser technology. The emitted electrons are accelerated in the near-electrode high electric field, becoming fast and capable of exciting the laser ionic transitions in the He (or Ne)-metal vapor or the He (or Ne)-rare gas mixtures, similarly as in the HCD. As in the HCD, a relatively high fraction of the low-ionization-potential lasing component can be introduced into the CCRF discharge, without decreasing the number of fast electrons, and therefore without reduction of the lasing capability of the discharge [10].

These special properties of the CCRF discharges have been employed for generating of a considerable number of visible and infrared ionic transitions in Tl [10], [11], Cd [10]–[20], Zn [10], [11], [21], [22], Hg [10], [11], [23], Se [10], [11], [18], [24], Cu [10], [25], Kr [18], [20], [26] and Ar [20].

Despite the correspondence between the hollow-cathode and CCRF discharges, the CCRF-excited lasers show some superiority over the lasers excited by the HCD's. This superiority results from higher longitudinal homogeneity of the discharge, more efficient transforming of the input power into the energy of the high-energy electrons, simplicity of the laser design, absence of arc formation at higher input powers, and the possibility of using external electrodes, which enable work with substances of high chemical activity.

Most of the research on the CCRF-excited lasers has concerned the He–Cd$^+$ laser system, which has attracted interest because of its capability of emitting the three primary spectral lines. 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, the introduction of the wall-originated particles into the discharge and the insufficient control of the Cd vapor density have limited the investigations mainly to a quasi-CW or pulsed regime. Actually, as yet no CW CCRF-excited He–Cd$^+$ laser which assured good stability and long operating lifetime has been reported.

We present the results of our effort to develop a simple CCRF-excited white-light He–Cd$^+$ laser, exhibiting long-life and stable generation in CW regime at tens milliwatt output power levels for the three primary lines. The long-life and stable operation of the CCRF-excited white-light He–Cd$^+$ laser was achieved mainly through the use of an alumina ceramic (Al_2O_3) discharge tube instead of the fused silica tube commonly employed in the past. The Al_2O_3 tube is less susceptible to damage by overheating and ion bombardment than that made of fused silica. Therefore less particle and gas impurities are released from the wall of the Al_2O_3 tube during operation of the discharge. More specific details on this subject, as well as on the discharge tube design and operation of the CCRF-excited white-light He–Cd$^+$ laser are given in [27].The results presented here may also be relevant, if the application of radio-frequency (RF) excitation to the generation of laser UV radiation on ionic transitions of metal or rare gas elements is considered.

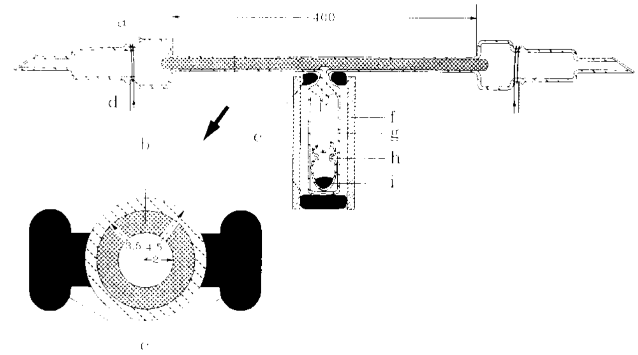

Fig. 1. Design of the CCRF-excited He–Cd$^+$ laser tube with Al_2O_3 capillary tube insert: a—fused silica tube, b—Al_2O_3 capillary tube, c—RF electrodes, d—heaters, e—insulating material, f—oven, g—Cd reservoir, h—ampoule, i—cadmium.

II. Experiment

A. Designs of the CCRF-Excited He–Cd$^+$ Laser Tube and Electrical Matching Circuit

The severe technological problems, associated with the existing designs of the CCRF-excited white light He–Cd$^+$ lasers made them unattractive. These problems include damage by overheating the laser tube, deterioration of the inner surface of the fused silica tube by ion bombardment and by the formation of a coarse layer of cadmium silicate, pollution of the gas fill by wall-originated particles and insufficient control of the Cd vapor density in the discharge zone. For practical realization of a long-life CW CCRF-excited white-light He–Cd$^+$ laser we have developed a laser tube, the design of which is shown in Fig. 1. The laser tube, the envelope of which was made of fused silica has a relatively simple design, even simpler than that of commonly available positive column He–Cd$^+$ lasers. A capillary tube made of Al_2O_3 was inserted symmetrically into the fused silica capillary tube, forming the active part of the laser tube. The length and inner diameter of the Al_2O_3 capillary tube were 400 mm and 4 mm, respectively.

The sputtering of the Al_2O_3 ceramic is much lower than that of the fused silica (by a factor of 7.5 when the sputtering by Ar^+ ions is considered [28]). Thus, using the Al_2O_3 capillary tube avoided the sputter-originated problems and resulted in a stable continuous operation of the laser. However, one must be aware of two negative factors caused by insertion of the Al_2O_3 capillary tube into the fused silica tubing. First, the higher temperature of the Al_2O_3 capillary tube which resulted by using the fused silica envelope can lead to a so called local overheating runaway effect.This is due to a significant increase in the dielectric loss of the Al_2O_3 ceramic where the temperature happens to be higher than 700 K. To prevent such a local overheating of the Al_2O_3 tube, the electrodes for supplying the RF power to the tube were of copper and were in direct contact along the fused silica tube. This ensured a uniform temperature distribution along the tube. The 400-mm-long and 4-mm-wide copper electrodes were nickel plated to prevent their oxidation. Second, parasitic discharges between the outer wall of the Al_2O_3 capillary tube and the inner wall of the fused silica tube can appear at higher RF input power and at higher He pressures, causing deterioration and malfunctioning of the laser tube. The manufacture of the He–Cd^+ laser tube with its active part consisting solely of an Al_2O_3 capillary tube without any outer tubing to avoid the parasitic discharges is possible but difficult. Such a tube is unreliable so far because its design requires several ceramic-fused silica transitions.

Cd vapor was supplied into the active part of the laser tube through a hole made in the Al_2O_3 capillary tube from a fused silica sidearm Cd reservoir with oven connected to the middle of the fused silica capillary tube. The Cd vapor diffused along the CCRF discharge in the Al_2O_3 capillary tube and deposited on the inner walls of the wide-diameter extension stubs, which served as condensation regions. Although we did not measure the distribution of the Cd vapor along the Al_2O_3 capillary tube, it seems to be axially uniform.This was checked by using five Cd reservoirs, distributed uniformly along the Al_2O_3 capillary tube and operated in an on- and off-mode. The higher number of the Cd reservoirs did not result in increased output power of the laser [18]. Such a behavior is in contrast with the theory of diffusion of Cd vapor in a laser tube [29]. During operation the temperature of the Cd reservoir was stabilized within ± 0.5 K.

The fused silica Brewster windows were sealed by soldering them to the fused silica narrow-diameter extension stubs. Thus, initially the cadmium was sealed in a vacuum-tight ampoule, so that the entire laser tube could be baked under vacuum to about 750 K. To protect the Brewster windows from deposition of the particles sputtered from the Al_2O_3 tube, electrically heated wires were wound around the condensation stubs. The heated wires produced thermal buoyancy whirls of the operating gas within the condensation region. The convective gas whirls deflected the travelling particles onto the walls of the stubs, thus avoiding contamination of the Brewster windows.

The RF power was capacitively coupled into the discharge established inside the Al_2O_3 capillary tube with the transverse copper electrodes mounted along the fused silica capillary tube with ceramic holders. 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 Z_D 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 $Z_D = (19.5 - j\,497.3)$ Ω at a RF generator output power of $P_g = 400$ W and He pressure of 30 mbar. 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 of the so-called γ-type of the CCRF discharge [9].

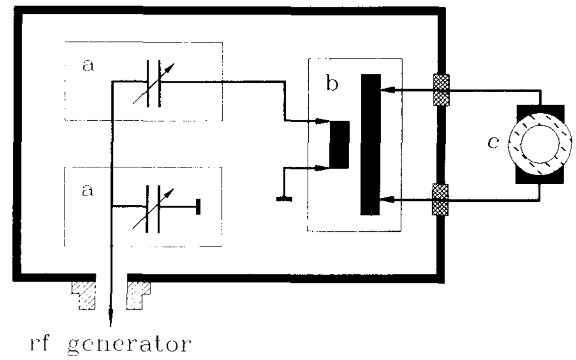

Fig. 2. Electrical circuit supplying RF power to the He–Cd^+laser tube: a—capacitor (45–650 pF), b—symmetrizing transformer, c—laser tube with electrodes.

B. Measuring Procedure

The experiment comprised investigations of the operating characteristics of the CCRF-excited He–Cd^+ laser under single- and multi-line operation mode, the small signal gain on each of the 441.6, 533.7, 537.8, and 635.5/636.0 nm transitions, the power interaction between oscillations at the He–Cd^+ laser transitions, and the noise of the laser output power.

The operating characteristics of the CCRF He–Cd^+ laser under single-line operation mode were measured with the setup similar to that described in [30]. Briefly, a laser resonator was formed by a high reflectivity ($R > 99.5\%$) mirror pair, set about 90 cm apart. For each color, blue, green, or red a selective narrow-band mirror pair was used. The radius of curvature of each mirror was 2 m. No attempt was made to optimize the mirror radii for maximum laser power extraction from the optically active volume of the laser. To separate each of the green lines ($\lambda = 533.7$ nm and $\lambda = 537.8$ nm) a birefringent Lyot filter [31] was inserted in the resonator. Besides the birefringent filter, a computerized assembly was placed inside the resonator. The assembly consisted of two contra-rotating Fresnel plates in order to produce either a variable output coupling or insertion loss for measuring small-signal gains on the laser transitions, and of a Fresnel plate tilted near Brewster angle to decouple a small part of the laser intra-resonator power for recording. A photodetector placed outside the laser resonator was used to record the outcoupled laser intra-resonator power. To eliminate a source of systematic error a polarizer transmitting, only the light polarized parallel to the plane of incidence of the laser intra-resonator beam onto the outcoupling Fresnel plate was placed in front of the photodetector. The combined intensities of the red lines were

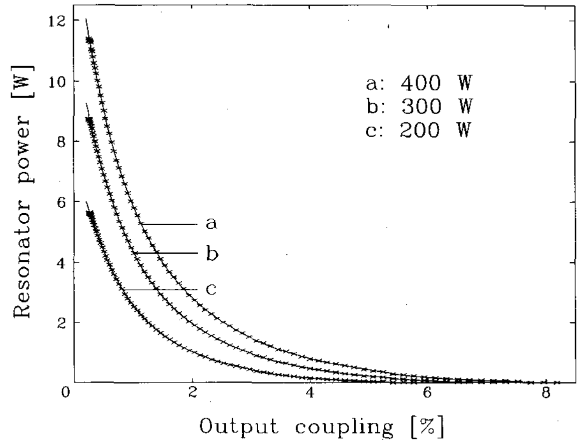

Fig. 3. He–Cd$^+$ laser intra-resonator power at $\lambda = 441.6$ nm as a function of output coupling for different RF input powers. He pressure −2.1 kPa.

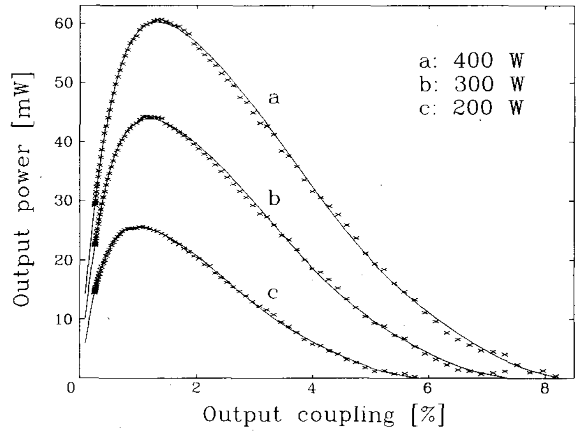

Fig. 4. He–Cd$^+$ laser output power at $\lambda = 441.6$ nm as a function of output coupling for different RF input powers. He pressure −2.1 kPa.

measured. Taking into account the output coupling of the two contra-rotating and the fixed Fresnel plates and the losses of the laser mirrors, the total output coupling of the laser intra-resonator power could be calculated. The laser output power as a function of output coupling was determined from the product of the measured laser intra-resonator power and the total output coupling.

Examples of the output-coupling-dependencies of the laser intra-resonator and output powers at $\lambda = 441.6$ nm for different input RF powers, resulting from the above procedure, are shown in Fig. 3 and Fig. 4, respectively. Similar curves not shown were plotted for the other laser lines. The optimum output coupling, the maximum laser output power and the small signal gain for each line could be evaluated from those curves.

Power interaction between oscillations at the He–Cd$^+$ laser transitions has been demonstrated experimentally in HCD He–Cd$^+$ laser systems, using a three-mirror resonator [32] or a birefringent filter [33] as a laser line selecting element. Those experiments showed a significant increase in the laser output power at the red and green lines when oscillating simultaneously. Such a behavior is of a high importance since there is a need to increase the output power of the He–Cd$^+$ laser at the red and green transitions to achieve a well-balanced color operation as a white-light laser. The optimum ratio of the He–Cd$^+$ laser powers of the red, green and blue lines for best quality of a white-light laser beam is $1:0.23:0.17$ [27]. Unfortunately, in the case of both HCD- and CCRF-excited He–Cd$^+$ lasers, this requirement is not met. The laser output power of the red lines is usually lowest , while the laser output power of the blue line is highest.

Our investigations on the multi-line operation of the CCRF-excited He–Cd$^+$ laser and on the influence of the green laser oscillations upon the laser output power at red and blue were performed using a double laser resonator with three mirrors of different selectivities for the three colors [34]. The double laser resonator (Fig. 5) consisted of an inner resonator for the blue (B) and both red (R) lines, and of an outer resonator for both green (G) lines. Both resonators had a common broad-band mirror M1. The inner resonator was terminated by a mirror M2 having high reflectivity for the blue and both red lines, and high transmittivity for both green lines. The outer resonator was terminated by a mirror M3 with a high reflectivity for both green lines. By tilting the mirror M3 from its optimum position, diffraction losses were produced, whereby the intra-resonator laser power at green could be varied, and influence of the green laser oscillations on the intra-resonator laser powers at blue and red could be investigated. The tilting of the mirror M3 had no mechanical effect upon the operation of the inner resonator. Since the mirrors M1 and M3 had a low residual transmittivity for all the laser lines, the powers of the transmitted laser lines, proportional to the corresponding intra-resonator powers could be monitored by two detectors, as shown in Fig. 5. Using the computerized assembly with two contra-rotating and one outcoupling Fresnel plates, inserted into the inner resonator, it was also possible to determine the laser output powers versus output coupling under power interaction of the laser lines.

As mentioned in the introduction, a very low laser output power noise is an important advantage of using CCRF discharges for laser excitation. In this experiment the noise of the laser output power at the blue wavelength was detected with a p-i-n photodiode. Since the main part of the laser output power noise occurs at low frequencies and no modulation of the laser output power at 13.56 MHz was observed, the noise spectrum was recorded with a spectrum analyzer (FSBS, Rhode & Schwarz) in the frequency range from 70 Hz to 1.5 MHz. The laser output power noise, evaluated from these recordings and divided by the average laser output power gave the noise-to signal ratio of the laser output power. This value was compared with the value of the noise-to-signal ratio indicated by a digital oscilloscope (9450, LeCroy) fed by the photodiode signal.

III. Results

The CCRF-excited white-light He–Cd$^+$ laser exhibited CW single- or multiline operation at seven wavelengths in the blue ($\lambda = 441.6$ nm), green ($\lambda = 533.7$ nm and $\lambda = 537.8$ nm), red ($\lambda = 633.5$ nm and $\lambda = 636.0$ nm) and infrared ($\lambda = 723.8$ nm and $\lambda = 728.4$ nm) regions. The laser operated at He

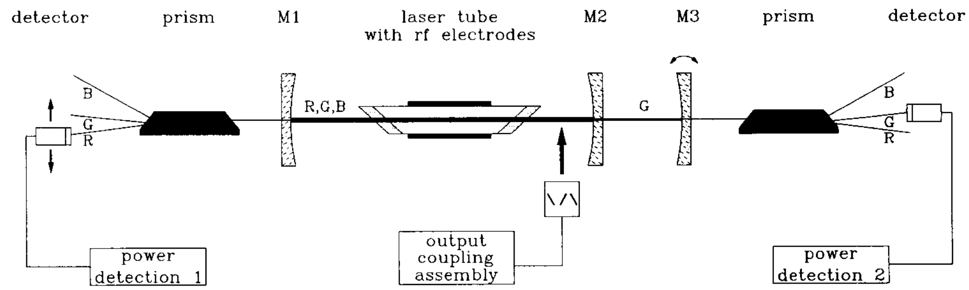

Fig. 5. Scheme of the double resonator with the inner and outer resonator formed by mirrors M1 and M2, and M1 and M3, respectively.

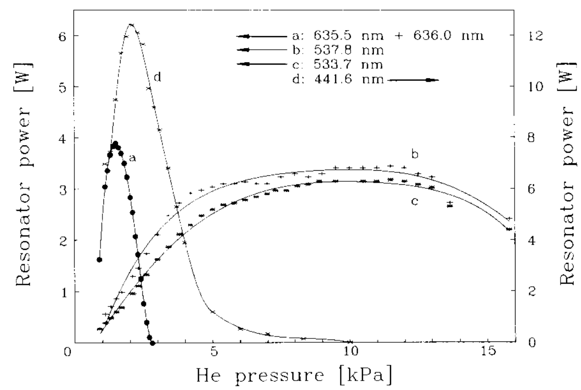

Fig. 6. He–Cd$^+$ laser intra-resonator power at $\lambda = 441.6$ nm, $\lambda = 533.7$ nm, $\lambda = 537.8$ nm, and $\lambda = 635.5$ nm and 636 nm as a function of helium pressure. RF input power -400 W.

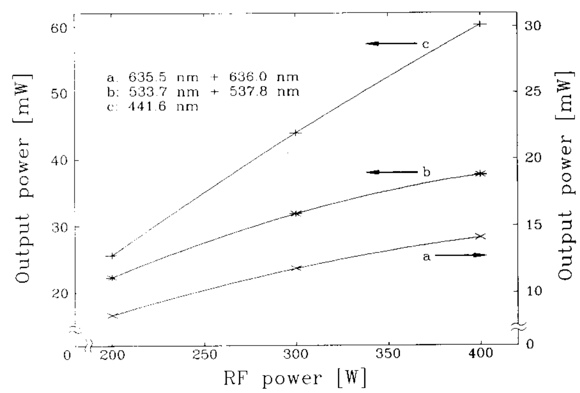

Fig. 7. He–Cd$^+$ laser output power at $\lambda = 441.6$ nm, $\lambda = 533.7$ nm and 537.8 nm, and $\lambda = 635.5$ nm and 636.0 nm as a function of RF input power.

pressures in the range from 1.5 kPa to 16 kPa, depending on the oscillation wavelength. The optimum Cd vapor pressure, estimated from the Cd reservoir temperature was about 80 Pa. All the results presented here were obtained for this Cd vapor pressure.

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. 6. It is seen that the laser intra-resonator powers of the red and blue lines exhibit narrow maxima at He pressures around 1.6 kPa and 2.1 kPa, respectively, while for each green line exists a broad maximum of the intra-resonator power ranging from 5 kPa to 15 kPa. Similar behaviors were observed for the intra-resonator powers of the HCD white-light He–Cd$^+$ laser operating in the single-line mode [33]. At its optimum He pressure the laser intra-resonator power of the blue line is more than 3 times higher than those, mutually comparable, intra-resonator powers of the red and green lines at their optimum He pressures. At He pressures which enable multi-line operation of the CCRF-excited He–Cd$^+$ laser (range from 1 kPa to 2.6 kPa) the laser intra-resonator powers under single-line operation at the blue line is clearly higher than those of the red and green lines. This is unfavorable, if a well-balanced color operation of the laser is desired.

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. 7. In Fig. 7, the operating He pressure for each laser line is different and corresponds to the optimum output power of the relevant line (see Fig. 6). As seen from Fig. 7, 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 [35], [36].

Fig. 8 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. 7. The small-signal gains of the green and red lines show some saturation with increasing RF 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 $\lambda = 537.8$ nm and 533.7 nm and the stronger red line $\lambda = 636$ nm, respectively. These results are similar to those obtained for the HCD He–Cd$^+$ lasers [3, 33, 37]. The small signal gains for the infrared lines $\lambda = 723.7$ nm and 728.4 nm were 1.6% m^{-1} and 2.3% m^{-1}, respectively.

Although the small signal gains of both green lines were higher than that of the blue line, the laser output power of the blue line was higher. The effect is due to the saturation parameters which are lower for the green lines than for the blue line. The saturation parameters are determined among other things by the rates of processes competing with induced emission and by the number of resonator modes which oscillate simultaneously at the laser transition. It is not clear at the moment which effects are responsible for the different saturation parameters of the green and blue lines.

The experiments carried out with the double laser resonator on multiline operation of the CCRF-excited He–Cd$^+$ laser

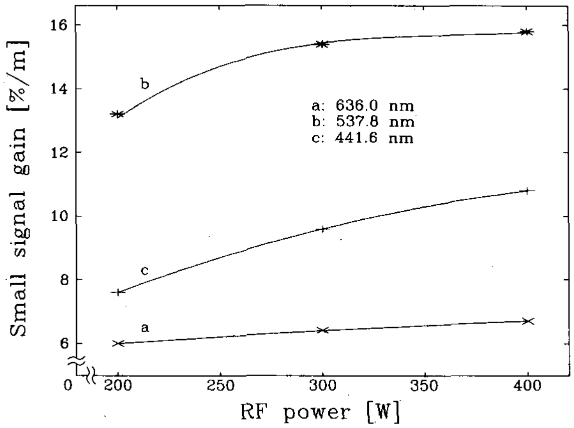

Fig. 8. Coefficients of the small-signal gain for $\lambda = 441.6$ nm, $\lambda = 537.8$ nm, and $\lambda = 636.0$ nm as a function of RF input power.

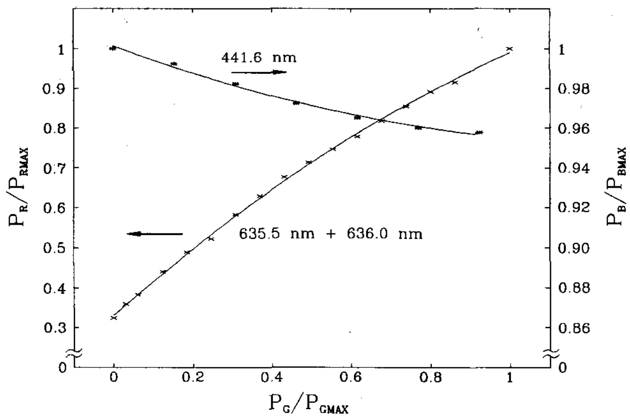

Fig. 9. Influence of the He–Cd^+ laser intra-resonator power at $\lambda = 533.7$ nm and 537.8 nm (P_G) upon the He–Cd^+ intra-resonator laser output powers at $\lambda = 441.6$ nm (P_B) and $\lambda = 635.5$ nm and 636.0 nm (P_R). P_{GMAX}, P_{BMAX}, and P_{RMAX} are the maximum values of the laser intra-resonator powers of the corresponding lines.

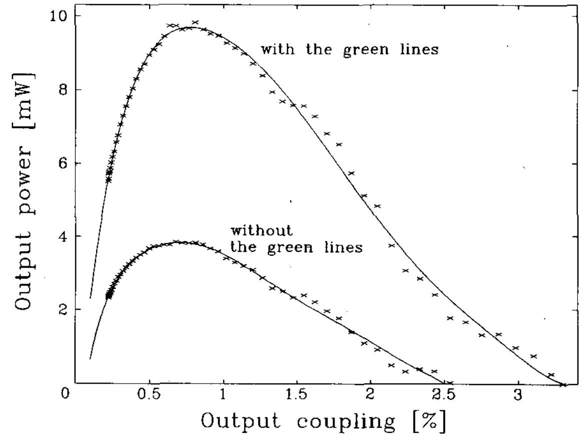

Fig. 10. He–Cd^+ laser output power at $\lambda = 635.5$ nm and 636.0 nm as a function of output coupling for single-line operation and simultaneous oscillations with the green lines ($\lambda = 533.7$ nm and 537.8 nm).

showed a significant increase in the output power of both red lines when they oscillated simultaneously with the green lines (Figs. 9 and 10). As seen from Figs. 9 and 10 the intensities of both red lines can be increased several times owing to the influence of the green lines. This result is in agreement with that obtained earlier in the HCD He–Cd^+ laser system [33]. Such an influence of the green oscillations on the red ones seems reasonable, taking into account that oscillations in the green de-populate the lower laser levels of the red transitions (for example, see [38]).

Apart from the power interaction between the green and red oscillations, we noticed a slight influence of the green oscillations on the intensity of the blue line. The intra-resonator laser power of the blue line decreased by 4% when the green and blue lines oscillated simultaneously (Fig. 9). This decrease in the intensity of the blue line can be explained by an increase in the population of the lower laser level of the blue transition, caused by the radiative cascades at $\lambda = 231.3$ nm and $\lambda = 232.1$ nm from the lower levels of the 537.8 nm and 533.7 nm laser transitions, respectively [39].

The observed increase in the laser output power of the red lines when they operate simultaneously with the green lines can be beneficial if the optimum white-light operation of CCRF-excited He–Cd^+ lasers is considered. Taking into account the results presented in Figs. 6 and 7, a maximum white-light laser output power (with a ratio of 1 : 0.23 : 0.17 for intensities of both red lines, both green lines and the blue line, respectively) of about 20 mW could be inferred if the lines operate separately. However, this value can be increased by a factor of two or three owing to the positive influence of the green oscillations on the laser output power of the red lines, and vice-versa as shown in [32], [33].

An important result of our investigation, showing low-noise operation of the CCRF-excited He–Cd^+ laser, is given in Fig. 11. Fig. 11 shows the noise spectra of the laser output powers at $\lambda = 441.6$ nm of the presented CCRF-excited He–Cd^+ laser and, for comparison, of a typical positive-column He–Cd^+ laser. At frequencies lower than 1 MHz the noise power of the CCRF-excited He–Cd^+ laser is at least 15 dB lower than that of the positive column one. Above 1 MHz the difference disappears and the measured values correspond to the internal noise of the spectrum analyzer. The noise-to-signal ratio of the laser output power of the CCRF-excited He–Cd^+ laser, lower than 0.4%, is comparable to that of the HCD He–Cd^+ laser [3], [5] but significantly lower than that of the positive-column one (about 7%). The laser output power noise in positive column lasers is generated by striations travelling along the discharge tube axis. If so, the low-noise operation of the CCRF-excited He–Cd^+ laser may suggest absence of the striations along the column of the CCRF-excited discharges.

The investigations described above have been performed during more than 400 hours. No significant deterioration of either the laser tube or the CCRF discharge has been observed during that period. However, the laser tube has been connected to the vacuum and gas-filling apparatus all the time, thus such negative effects as leakage or clean-up of helium, outcoming of impurity gases from the tube walls, etc. have not influenced operation of the laser tube. The consumption of cadmium during 400-hour operation of the CCRF-excited He–Cd^+ laser was 1.5 g. After the 400-hour operation the laser tube was sealed-off with helium in it, and set aside. About two

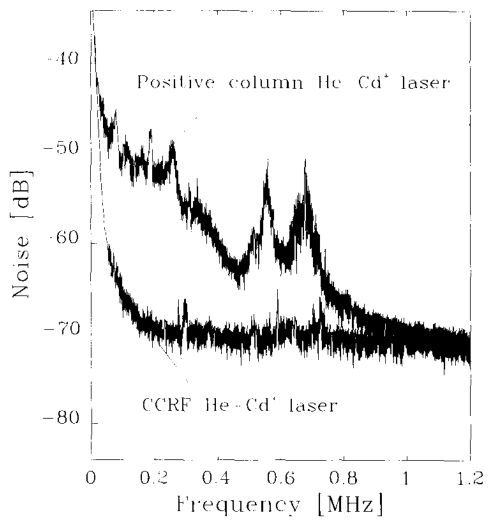

Fig. 11. Noise spectra of the CCRF-excited and positive column He–Cd^+ lasers.

months later the laser tube was put into operation again. After discharge ignition the tube generated all the laser lines with approximately the same intensities as before. The above allows inferring that a long-life He–Cd^+ laser can be built when the CCRF discharge is used for its excitation.

IV. Conclusion

In these experiments it was shown that the CCRF discharge is capable of efficient exciting CW multicolor He–Cd^+ laser operation at seven wavelengths in blue ($\lambda = 441.6$ nm), green ($\lambda = 533.7$ nm and $\lambda = 537.8$ nm), red ($\lambda = 635.5$ nm and $\lambda = 636.0$ nm) and infrared ($\lambda = 723.8$ nm and $\lambda = 728.4$ nm) regions. Under single-line operation excited with a RF input power of 400 W the laser output powers of 60 mW, 38 mW, and 14 mW were obtained for the blue, green and red lines, respectively. The laser output power in red (and also in green [32], [33]) can be increased by a factor of 3, if all lines operate simultaneously. This is owing to the power interaction between oscillations at the red and green transitions of the He–Cd^+ laser. The measurements showed that owing to this interaction the white-light operation of the CCRF-excited He–Cd^+ laser with a total output power of about 60 mW is possible.

The laser output powers and small-signal gains (11% m^{-1}, 16% m^{-1}, and 7% m^{-1} for the blue, stronger green and stronger red lines, respectively) obtained in the CCRF-excited He–Cd^+ lasers are comparable to the record values obtained for the HCD He–Cd^+ lasers of the same active length. Therefore, as far as the laser output power level is concerned the CCRF-excited He–Cd^+ laser shows no inferiority to the lasers excited by HCD's. However, the output powers comparable to those of the HCD He–Cd^+ lasers are obtainable using the CCRF-excited He–Cd^+ laser 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 He–Cd^+ 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 outside the discharge tube, shorter starting time compared to that of HCD He–Cd^+ lasers, relatively low noise of the laser output power (noise-to-signal ratio lower than 0.4%).

Owing to the Al_2O_3 capillary tube the CCRF-excited He–Cd^+ laser 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^+ laser should be useful as a simple, long-lived, continuously operating, white-light laser source operating at tens miliwatts output power levels.

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