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The performance of the hollow-cathode discharge continuous-wave multicolour He–Cd$^+$ laser

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Abstract. We report on the performance of a hollow-cathode discharge continuous wave He–Cd$^+$ laser module, which is capable of simultaneously delivering stable, milliwatt output power at the three primary spectral lines: blue (λ = 441.6 nm), green (λ = 533.7 and 537.8 nm), and red (λ = 635.5 and 636.0 nm). In particular, the laser output characteristics for single- and multi-line operation and the power interaction between the laser lines are presented. The results show that the most efficient simultaneous laser oscillations at the red, green and blue lines occur for the He pressure (8 mbar at an inner diameter of the hollow cathode of 4 mm) at which the hollow-cathode effect is strongest. We find strong power interaction between the green and red lines, showing experimentally that, apart from the already known increase in the He–Cd$^+$ laser output power in the green owing to the radiative cascade transitions in the red, also the red lines gain in their output power under simultaneous operation with the green lines, which de-populate the lower laser levels of the red transitions. Under some conditions the de-population of the lower laser levels of the red transitions by the green lines' oscillations can be the dominant mechanism for the build-up of the population inversion between the upper and lower levels of the red transitions.

1. Introduction

Since its first introduction (Karabut *et al* 1969, Sugawara and Tokiwa 1970, Sugawara *et al* 1970, Schuebel 1970a, b) the hollow-cathode discharge (HCD) He–Cd$^+$ laser has become a very promising candidate for a multicolour laser system. From the 11 laser lines generated under CW operation by the HCD He–Cd$^+$ laser in the spectral range 325.0–887.8 nm (Willett 1974) the simultaneously generated blue (λ = 441.6 nm), green (λ = 533.7 and 537.8 nm) and red (λ = 635.5 and 636.0 nm) lines are of interest for colour information processing technology. The wavelengths of these lines are close to those of the three ideal primary spectral lines (λ = 450, 540 and 610 nm (Thornton 1971)). Owing to this, the colour of the HCD He–Cd$^+$ laser beam can be varied over a wide range, including white colour, after a proper mixing of the red, green and blue laser lines. Despite the permanent demand for such a multicolour laser, there is at present no multicolour HCD He–Cd$^+$ laser device available on the laser market, mainly because of the problems with manufacture, stability and maintenance of the HCD laser systems.

We have recently reported the design features of a 10 cm active length HCD CW multicolour He–Cd$^+$ laser module, which, owing to the particular cathode design, laser tube conditioning and thermal instability precaution employed, is capable of simultaneously delivering stable, milliwatt power output at the three primary spectral lines (Mizeraczyk *et al* 1994). Owing to this stable operation of the laser, we were able to investigate the output power characteristics of each laser line reliably in single- or multi-line operation using a birefringent filter (Mentel *et al* 1992). As a result, some interesting characteristics of the HCD He–Cd$^+$ laser operation, corresponding to power interaction of the laser lines, were obtained. These characteristics showed some correspondence between the performances of the HCD He–Cd$^+$ laser and a He–Cd$^+$ laser excited transversely by capacitively coupled radio-frequency (CCRF) power (Reich *et al* 1994), and therefore they are also of importance for the practical development of He–Cd$^+$ laser systems excited by CCRF power. In the near future, the CCRF-excited He–metal vapour ion lasers may become competitors to those excited in the HCDs.

2. Experiment

The detailed design of the HCD CW multicolour He–Cd$^+$

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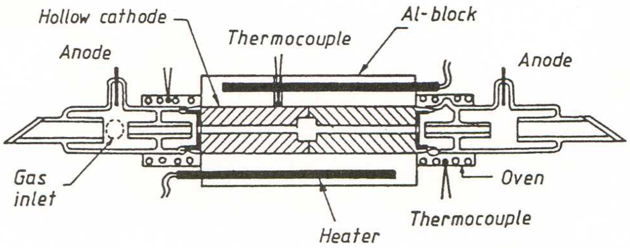

Figure 1. The scheme of the hollow-cathode discharge He–Cd$^+$ laser module.

laser module used in this experiment has been described elsewhere (Mizeraczyk *et al* 1994). The simplified scheme of the laser module is shown in figure 1. The module consisted of two anodes and a hollow cathode located between them. Two long, narrow cylinders (50 mm long and 4 mm in diameter) separated by a wider cylinder (10 mm long and 10 mm in diameter) were made in the hollow cathode. The narrow cylinders served as hollow cathodes, while the wider cylinder efficiently stabilized the discharges in the narrow cathode cylinders, making them spatially similar. The active length of the laser module was 10 cm. Cadmium was introduced into the hollow cathode in the form of a thin layer covering its inner walls. A heavy-wall Al cylinder, with electrical heaters placed in it, was mounted in intimate thermal contact with the hollow cathode. Owing to a large outer area of this cylinder, the heat produced by the discharge in the hollow cathode was effectively dissipated so that the discharge current played a minor role in controlling the temperature of the hollow cathode. The hollow-cathode temperature, determining the Cd vapour pressure in the hollow cathode (Roth 1976), was mainly controlled by the electrical heaters, rather independently from the discharge current. Owing to the particular cathode design the laser module has exhibited stable operation for more than 300 h. The short- and long-term laser output power variations were less than 1% (peak-to-peak).

The discharge was supplied through two 2.5 kΩ resistors ballasting each anode from a DC power source. The typical discharge current flowing to each anode was 130 mA, with long-term fluctuations less than ± 5 mA. The temperature of the hollow cathode was stabilized within ± 0.5 K. For stabilization of the laser output power, we chose to refer not to the hollow-cathode temperature but to the voltage drop between the anode and cathode, since we found that the voltage drop response to the variation in the discharge condition was faster than that of the thermocouple used for measuring the hollow-cathode temperature.

The operating characteristics of the HCD He–Cd$^+$ laser module were measured with the set-up shown in figure 2. The laser resonator was formed by a high-reflectivity ($R > 99.9\%$) broadband mirror pair, set about 70 cm apart. The radius of curvature of both the mirrors was 1.5 m. No attempt was made to optimize the curvature radii of the mirrors for maximum laser power extraction from the optically active volume of the laser. Inside the resonator were placed a computerized

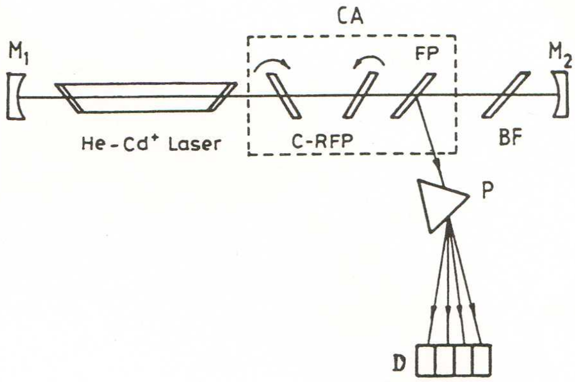

Figure 2. Experimental set-up: M_1 and M_2, mirrors; CA, computerized assembly for small-signal gain measurement; C-RFP, contra-rotating Fresnel plates; FP, Fresnel plate; BF, birefringent filter; P, prism; and D, set of photodetectors.

assembly that uses 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 a Fresnel plate tilted near Brewster angle for recording the intra-resonator laser power (Reich *et al* 1991). For selection of a laser line and choosing either single- or multi-line operation, a birefringent filter was also inserted in the resonator. A prism and a set of four photodetectors placed outside the laser resonator were used for dispersion of the laser beam into individual lines and their intensity detection. The intensities of both red, as well as both infrared, lines were measured in total. The laser output power and its maximum were calculated from the product of the measured resonator power and the output coupling of the three plates, using Fresnel equations.

The parametric investigation of operation of the HCD He–Cd$^+$ laser module was carried out using the Fresnel plate, set (at almost Brewster angle to minimize the insertion losses) in the laser resonator (figure 2) for recording behaviours of the intra-resonator laser powers when changing operating parameters. Therefore, in the figures related to this investigation the intra-resonator laser powers are shown in arbitrary units. The laser output powers under optimum discharge conditions were measured in absolute units with the set-up given in figure 2. For clarity their maximum values are also given in the captions to the figures, which show behaviours of the intra-resonator laser powers in arbitrary units.

3. Operating characteristics of the hollow-cathode discharge He–Cd$^+$ laser

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

The HCD He–Cd$^+$ laser combined resonator power for both green lines, $\lambda = 533.7$ and 537.8 nm, and the operating voltage as a function of hollow-cathode

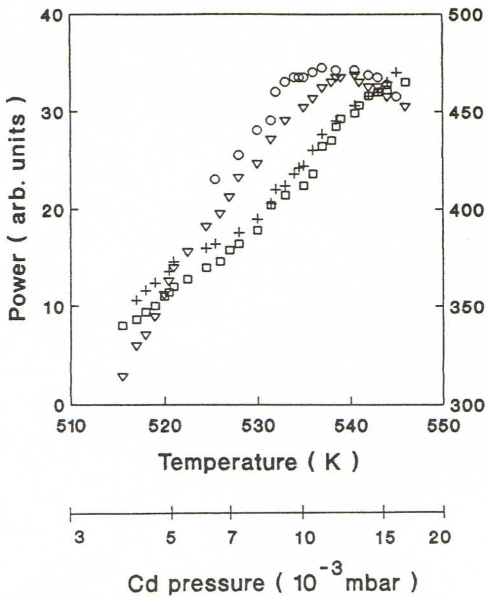

Figure 3. The He–Cd$^+$ laser combined resonator power (○, ▽) at $\lambda = 533.7$ and 537.8 nm, and operating voltage (+, □) as a function of hollow-cathode temperature (or Cd vapour pressure) for two different rates of increase in the hollow-cathode temperature. Points (○) and (+) correspond to faster increasing temperature. The He pressure was 12 mbar and the total discharge current was 260 mA.

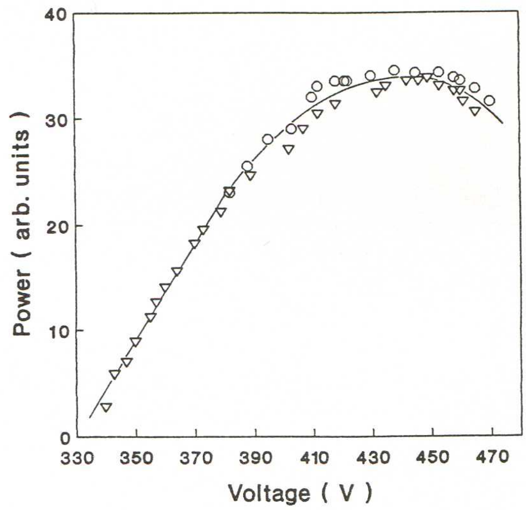

Figure 4. The He–Cd$^+$ laser combined resonator power at $\lambda = 533.7$ and 537.8 nm as a function of operating voltage for faster (○) and slower (▽) increase in the hollow-cathode temperature. The He pressure was 12 mbar and the total discharge current was 260 mA.

temperature, which determined Cd vapour pressure in the hollow cathode, are shown in figure 3 for two different rates of increase in the hollow-cathode temperature. It is consistent with the earlier measurements of Gill and Webb (1977) that the operating voltage increases with increasing temperature of the hollow cathode (and Cd vapour pressure in it). This fact was employed by us for controlling operation of the HCD He–Cd$^+$ laser. Moreover, we noticed that the operating voltage immediately follows changes in the discharge conditions, for instance those caused by variation of the discharge current or heating of the hollow cathode. In contrast, there was a time delay between the actual discharge condition variation and the measured hollow-cathode temperature due to the thermal inertia of the thermocouple set, which was placed in the hollow cathode wall and thus outside the discharge. Therefore, in the following text, as during the running of this experiment, we use the operating voltage rather than the hollow-cathode temperature as a practical variable that more reliably determines operation of the laser. This was shown in the experiment with two different rates of increase in the hollow-cathode temperature (figures 3 and 4). Anyone unaccustomed to using the operating voltage as a parameter should only remember that, under constant He pressure and discharge current, an increase in the operating voltage follows the increase in the Cd vapour pressure caused by the increase in the hollow-cathode temperature.

According to the partial energy-level diagram of Cd II (figure 5) the interaction between oscillations at the He–Cd$^+$ laser transitions is to be expected. Kawase (1979) found experimentally that the radiative cascade pumping of the upper lasing levels of the green lines by the red lines yielded in an increase in the output powers of both green lines. He also found that the oscillation at the blue line suppressed slightly the oscillations at the red and green lines. Kawase (1978, 1979) suggested that the laser oscillation at the blue line causes a decrease in the numbers of He atoms in the metastable $2\,^3S_1$ state (which is involved directly in excitation of the blue laser line (Silfvast 1971)) and He atoms in the metastable $2\,^1S_0$ and 'quasi-metastable' np ^{1}P and np ^{3}P states. Both of the latter are partly produced by collisions of the He atoms in the metastable $2\,^3S_1$ state with electrons. The number of the excited He atoms may affect the output powers of the red and green laser lines. The excitation of the red laser lines by charge-transfer reaction between He$^+$ ions and Cd atoms in the ground state (Webb *et al* 1970) depends on the number of He$^+$ ions, part of which is produced in the direct or step-wise ionization of the excited He atoms. As suggested by Kawase, one of the potential mechanisms of excitation of the green laser lines is Penning-like collisions of the He atoms in the quasi-metastable 3p ^{1}P and 3p ^{3}P states with Cd atoms in the ground state. Therefore, a decreasing number of the excited He atoms may result in the observed suppression of the laser oscillations at the red and green lines.

In this experiment, not only was an increase in the output power of the green lines when they oscillated simultaneously with the red ones confirmed, but also it was noticed that the simultaneous oscillations of the red and green lines resulted in the increased output power of the red lines. However, no influence of the blue line on the output powers of the other lines, and vice versa, was observed, although, to minimize possible errors, in our experiment the coupling between the laser lines was investigated without changing the laser resonator, differently to Kawase's (1979) case.

Figure 6 shows the pressure-dependence of the He–Cd$^+$ laser resonator power for the green (λ = 533.7

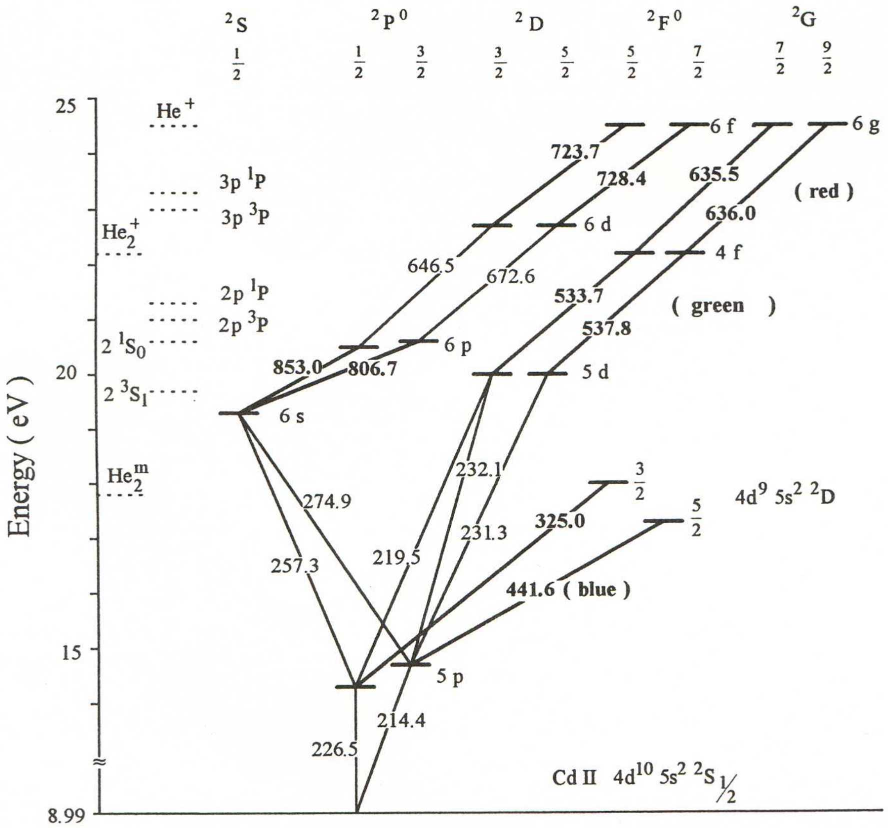

Figure 5. A partial energy-level diagram of Cd II and He with He–Cd$^+$ laser transitions (shown by bold lines). The wavelengths are given in nanometres.

and 537.8 nm) and red ($\lambda = 635.5$ and 636.0 nm) lines at constant hollow-cathode temperature and discharge current for single- and multi-line (all seven lines oscillate) operation. The resonator power of the laser red lines exhibits its maximum at around 8 mbar (here the values of He pressure refer to the initial He pressure at room temperature) regardless of whether single- or multi-line operation is involved. However, the laser red lines gain in intensity when they oscillate simultaneously with the green lines. Although such a behaviour seems reasonable, taking into account that oscillations in the green de-populate the lower laser levels of the red transitions (figure 5), to our knowledge no experimental demonstration of such an effect has been reported in the literature. Under optimum operating conditions the intensity of the red laser lines even doubles when 'reinforced' by the simultaneously oscillating green lines. The oscillations in the red cease at around 17 mbar for single-line operation but at around 22 mbar when they oscillate simultaneously with the green lines. The resonator power of the green lines exhibits two maxima. The first maximum coincides with the maximum for the resonator power of the red lines, that is, it occurs at around 8 mbar, regardless of the mode of operation. The second maximum occurs at around 40 mbar, which is far beyond the region of oscillation of the red lines. As was also earlier shown by Kawase (1979), both green lines gain in their intensity when they oscillate simultaneously with the red lines. This experiment showed (figure 6) that the resonator power of the stronger green line, $\lambda = 537.8$ nm, which is excited by the cascade transition of the red line $\lambda = 636.0$ nm, can increase even by a factor of two or more, whereas the resonator power of the weaker green line $\lambda = 533.7$ nm, which is excited by the other red laser line ($\lambda = 635.5$ nm), is not much affected. This does not contradict the results of Kawase (1979), which reported an increase in the intensity of the $\lambda = 533.7$ nm line by a factor of one and a half. The weakly marked increase in the resonator power of the $\lambda = 533.7$ nm line in our experiment can to some extent be explained by much lower resonator laser power of the $\lambda = 635.5$ nm line, compared with that in the experiment of Kawase (1979). The laser oscillations of the green lines cease at around 62 mbar. It is worth noting that, in the low-He-pressure region (below 20 mbar), the resonator power of the $\lambda = 537.8$ nm line is markedly higher than that of the $\lambda = 533.7$ nm line, whereas the resonator power of the two lines become equal at higher He pressures. The results shown in figure 6 can be explained by assuming that, at low He pressures, the green lines are mostly excited by cascade transitions of the red lines (Collins 1973, 1975), and at higher He pressures, by charge transfer from the molecular He_2^+ ions to 4f levels in Cd$^+$ ions (Wong and Grey Morgan 1983, Acosta-Ortiz *et al* 1993) and Penning-like reactions between He atoms in the quasi-metastable states 3p ^{1}P and 3p ^{3}P and the Cd atoms in the ground state (Kawase 1978, 1979). Presumably, within

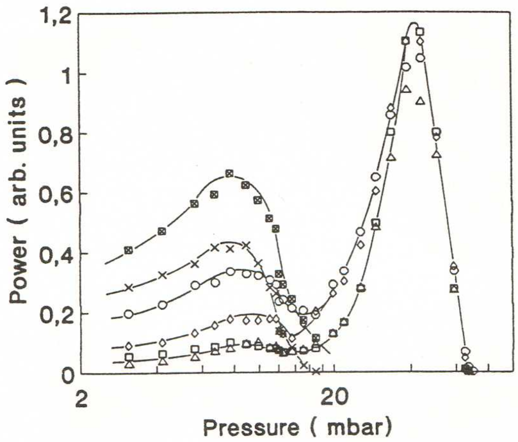

Figure 6. The He–Cd^+ laser resonator power at $\lambda = 533.7$, 537.8, 635.5 and 636.0 nm as a function of He pressure. The temperature of the hollow cathode was 533 K and the total discharge current was 260 mA. For single-line operation: (△), $\lambda = 533.7$ nm; (◇), $\lambda = 537.8$ nm; and (×), $\lambda = 635.5$ and 636.0 nm. For multi-line operation: (□), $\lambda = 533.7$ nm; (○), $\lambda = 537.8$ nm; (⊠), $\lambda = 635.5$ and 636.0 nm. At He pressure 8 mbar the laser output powers under multi-line operation were: 3 mW at 441.6 nm, 0.3 mW at 533.7 nm, 0.4 mW at 537.8 nm and 0.1 mW at both 635.5 and 636.0 nm.

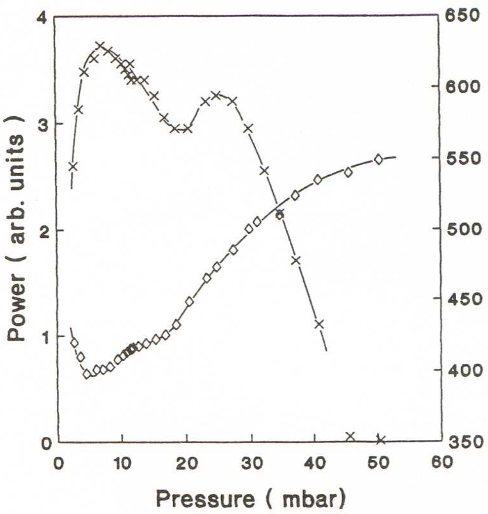

Figure 7. The He–Cd^+ laser resonator power (×) at $\lambda = 441.6$ nm and operating voltage (◇) as a function of He pressure. The temperature of the hollow cathode was 533 K and the total discharge current was 260 mA. At He pressure 8 mbar the laser output power at 441.6 nm was 3 mW.

the whole He pressure range, the green lines are also directly excited by charge transfer from He^+ ions, though the number of He^+ ions decreases with increasing He pressure in the HCDs (Mizeraczyk *et al* 1990).

The dependence of the laser resonator power of the blue line $\lambda = 441.6$ nm on He pressure also exhibits two maxima (figure 7), the first at around 8 mbar and the second at around 27 mbar. The first maximum coincides with the maxima of the resonator powers of the red and green laser lines in the low-He-pressure region. The oscillation in the blue ceases at around 45 mbar. In figure 7 the curve that illustrates changes in the operating voltage with increasing He pressure is also shown. Comparing the behaviour of this curve with those of the laser resonator powers as a function of He pressure (figures 6 and 7) shows that the low-He-pressure maxima of the laser resonator powers of the red, green and blue lines occur at the minimum of the operating voltage, namely when the hollow cathode effect is strongest (Rozsa 1980). The existence of the two maxima for the laser power in the blue region may be attributed to different discharge conditions, and thus different dominant excitation mechanisms, occurring in our hollow cathode when changing from low to high He pressures. In our laser tube the discharge enters the hollow cathode coaxially. This means that, at low He pressures (below 15 mbar), the discharge in the hollow cathode is of the so-called longitudinal HCD mode (Mizeraczyk 1983). The properties of the longitudinal HCD mode resemble those of the positive column of the glow discharge (Mizeraczyk 1985). At higher He pressures, the discharge in our hollow cathode becomes more similar to the so-called transverse mode of the HCD. In general, this mode occurs when the discharge current enters the hollow cathode radially. The characteristics of the transverse HCD mode correspond to those of the negative glow of the glow discharge. Change in the discharge conditions influences excitation mechanisms of the 441.6 nm Cd^+ ion laser transition, the upper level of which is believed to be populated by Penning collisions between He atoms in the metastable $2\,^3S$ state and Cd atoms in the ground state (Silfvast 1971), and by electron–Cd^+ ion collisions (Mori *et al* 1978). Possible change in mutual importance of these processes with variation of He pressure may be responsible for the two maxima of the HCD He–Cd^+ laser power at 441.6 nm observed in this experiment.

Since there are two regions of He pressures, low and high, in which the HCD He–Cd^+ laser resonator powers exhibit their maxima, we investigated operation of the laser in those regions separately.

The laser resonator powers as a function of operating voltage (or Cd vapour pressure) are shown for the green and red lines at low He pressure in figure 8, and for the green lines at high He pressure in figure 9. Figure 8 proves that the combined laser resonator power of the red lines and the laser resonator power of the stronger green line ($\lambda = 537.8$ nm) increase markedly when the red and green lines oscillate simultaneously. However, no laser resonator power reinforcement has been monitored for the weaker green line ($\lambda = 533.7$ nm). The laser resonator power of the red lines increases with increasing operating voltage (or Cd vapour pressure) at first, reaches its maximum (at around 387 and 395 V for single- and multi-line operation, respectively), and then decreases. The laser resonator powers of both green lines increase with increasing Cd vapour pressure, but the increase become very pronounced at a Cd vapour pressure higher than 0.02 mbar, corresponding to 450 V operating voltage. However, we could not further increase Cd vapour pressure, since the operating voltage became high and it made the discharge unstable. At higher He pressures (figure 9) the resonator laser powers of both

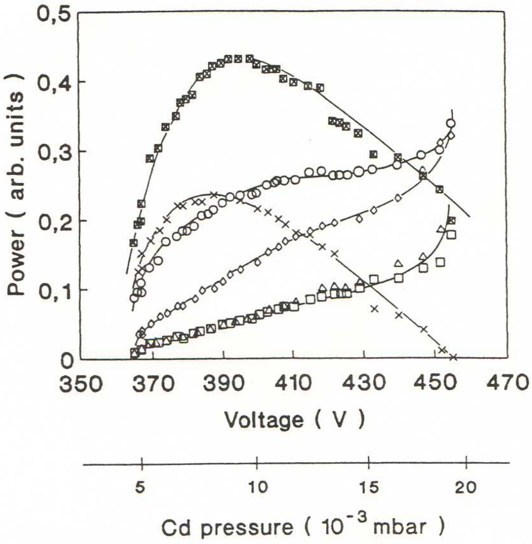

Figure 8. The He–Cd$^+$ laser resonator power at $\lambda = 533.7$, 537.8 and 635.5 plus 636.0 nm as a function of operating voltage (or Cd vapour pressure). The He pressure was 8 mbar and the total discharge current was 260 mA. For single-line operation: ($\triangle$), λ = 533.7 nm; ($\Diamond$), λ = 537.8 nm and ($\times$), λ = 635.5 and 636.0 nm. For multi-line operation: ($\square$), λ = 533.7 nm, ($\circ$), λ = 537.8 nm; and ($\boxtimes$), λ = 635.5 and 636.0 nm. Under Cd vapour pressure of about 0.01 mbar (operating voltage about 400 V) the laser output powers under multi-line operation were: 0.3 mW at 533.7 nm, 0.4 mW at 537.8 nm and 0.1 mW at both 635.5 nm and 636.0 nm.

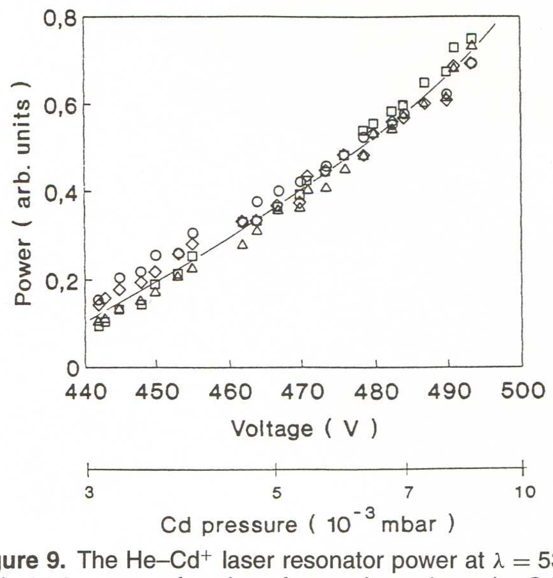

Figure 9. The He–Cd$^+$ laser resonator power at $\lambda = 533.7$ and 537.8 nm as a function of operating voltage (or Cd vapour pressure). The He pressure was 40 mbar and the total discharge current was 260 mA. For single-line operation: ($\triangle$), λ = 533.7 nm; and ($\Diamond$), λ = 537.8 nm. For simultaneous operation of both green lines:($\square$), λ = 533.7 nm; and ($\circ$), λ = 537.8 nm.

green lines increase with increasing Cd vapour pressure and no saturation is observed in the region tested. As could be expected, no difference in the resonator laser powers of the green lines occurs as they oscillate either as a single line or simultaneously.

The laser resonator power at the blue line λ = 441.6 nm and the operating voltage as a function of

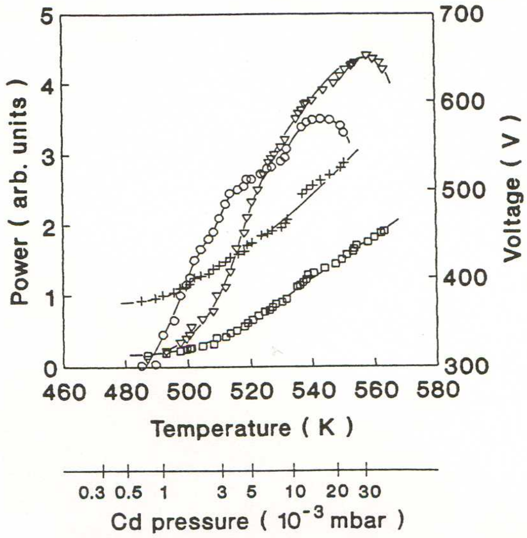

Figure 10. The He–Cd$^+$ laser resonator power at λ = 441.6 nm (∇), 7.5 mbar He; and ($\circ$), 26.7 mbar He) and operating voltage (($\square$), 7.5 mbar He; and (+), 26.7 mbar He) as a function of hollow-cathode temperature (or Cd vapour pressure). The total discharge current was 260 mA. At He pressure of 7.5 mbar and hollow-cathode temperature 531.5 K the laser output power at 441.6 nm was 3 mW.

hollow-cathode temperature (or Cd vapour pressure) for a low and a high He pressure are shown in figure 10. The operating voltage at the high He pressure (26.7 mbar) is always about 100 V higher than that at the low He pressure (7.5 mbar) regardless of the hollow-cathode temperature. The laser resonator power at λ = 441.6 nm increases with increasing Cd vapour pressure in the hollow cathode, reaches its maximum, and then decreases, regardless of He pressure. However, optimum Cd vapour pressure (about 0.026 mbar) at the low He pressure is higher than that (about 0.015 mbar) at the high He pressure. The maximum laser resonator power is higher at the low He pressure.

We did not find any influence of the other laser lines on the combined laser output power at both infrared wavelengths (λ = 723.8 and 728.4 nm), even under the operating condition in which the intensity of the red lines is strongly affected by the presence of the other laser lines (figure 11).

Discharge-current-dependences of the laser resonator powers for the green and red lines at low He pressure and for the green lines at high He pressure are shown in figure 12 and 13, respectively. It can be seen from figure 12 that the reinforcement of the red lines' intensity caused by the simultaneously oscillating green lines becomes more pronounced at higher discharge currents. In other words, at higher discharge currents the excitation of the laser oscillations at red transitions through de-population of their lower levels by the induced emission in the green is dominant. This strong influence of the green lines' oscillations on the laser resonator power in the red is the reason for a marked shift in optimum discharge current for single- and multi-line operation of the red lines. The optimum discharge currents are about 200 and 280 mA for

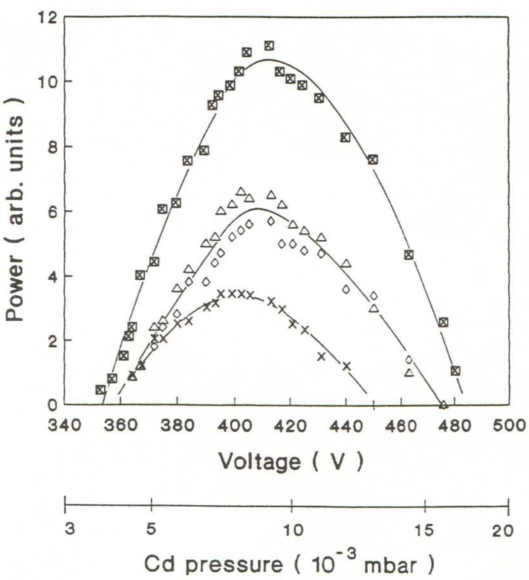

Figure 11. The He–Cd$^+$ laser resonator power at λ = 635.5 and 636.0 nm, and at λ = 723.8 and 728.4 nm as a function of operating voltage (or Cd vapour pressure). The He pressure was 12 mbar and the total discharge current was 260 mA. For single-line operation: (×), λ = 635.5 and 636.0 nm; (△), λ = 723.8 and 728.4 nm. For multi-mode operation: (⊠), λ = 635.5 and λ = 636.0 nm; and (◇), λ = 723.8 and 728.4 nm

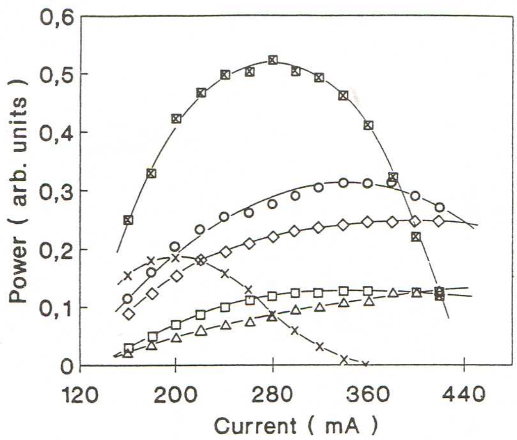

Figure 12. The He–Cd$^+$ laser resonator power at λ = 533.7, 537.8 and at λ = 635.5 and 636.0 nm as a function of total discharge current. The He pressure was 8 mbar and the hollow-cathode temperature was 532 K. For single-line operation: (△), λ = 533.7 nm; (◇), λ = 537.8 nm; (×), λ = 635.5 and 636.0 nm. For multi-line operation: (□), λ = 533.7 nm; (□), λ = 537.8 nm; and (⊠), λ = 635.5 and λ = 636.0 nm. Under total discharge current of 260 mA the laser output powers for multi-line operation were: 0.3 mW at 533.7 nm, 0.4 mW at 537.8 nm and 0.1 mW at both 635.5 and 636.0 nm.

single- and multi-line operation, respectively. Also, discharge currents at which oscillations of the red lines cease are clearly different for single- (360 mA) and multi-line operation (around 440 mA). In the low-He-pressure region the laser resonator power at λ = 537.8 nm under multi-line operation at first increases with increasing discharge current, reaches its maximum, and then slightly decreases. Under single-line operation the laser resonator power at λ = 537.8 nm after an initial

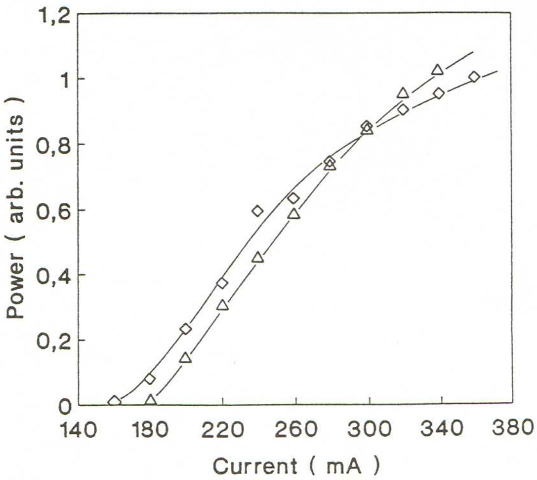

Figure 13. The He–Cd$^+$ laser resonator power under single-line operation at λ = 533.7 (△) and 537.8 nm (◇) as a function of total discharge current. The He pressure was 40 mbar, and the hollow-cathode temperature was 529 K.

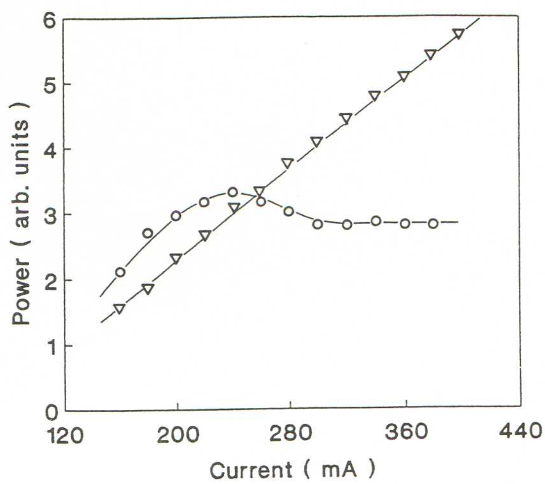

Figure 14. The He–Cd$^+$ laser resonator power at λ = 441.6 nm as a function of total discharge current for a low (▽, 7.5 mbar) and a high (○, 26.7 mbar) He pressure. The hollow-cathode temperature was 531.5 K. Under discharge current of 260 mA the laser output power at 441.6 nm was 3 mW.

increase with increasing discharge current, becomes saturated beyond 440 mA. The laser resonator power at λ = 533.7 nm behaves similarly. At higher He pressures (figure 13) the laser resonator powers of both green lines increase with increasing discharge current, showing a weak saturation at discharge currents as high as 400 mA. It is worth noting that the difference in resonator power between the two green lines, which is clearly present at low He pressures (figure 12), becomes less pronounced at higher He pressures. Moreover, at higher He pressures and total discharge currents higher than 300 mA, the line λ = 533.7 nm becomes stronger than the line λ = 537.8 nm. This difference in the behaviours of the two green lines at low and high He pressures indicates an essential variation in the excitation mechanism of the green lines with changing He pressure.

The laser resonator power at λ = 441.6 nm increases almost linearly with increasing discharge current at a low He pressure (7.5 mbar) (figure 14). At a discharge current of 400 mA the laser output power reaches almost 6 mW, which is rather high for a He–metal vapour ion laser with such a short active length. At a high He pressure (26.7 mbar) the laser resonator power in the blue increases at first, reaches its maximum at 260 mA, and then becomes saturated.

Under optimum conditions for multi-line operation (He pressure 8 mbar and Cd vapour pressure 0.01 mbar, corresponding to a hollow-cathode temperature of 533 K and operating voltage of 400 V, with total discharge current 260 mA) the output powers of the seven laser lines emitted were as follows: λ = 441.6 nm, 3 mW; λ = 533.7 nm, 0.3 mW; λ = 537.8 nm, 0.4 mW; λ = 635.5 and 636.0 nm, total 0.2 mW; and λ = 723.8 and 728.4 nm, total 0.1 mW. The corresponding small-signal gains were: 12, 11, 15, 4.5 and 3.7% m. All these values were obtained for higher order mode operation of the laser.

4. Concluding remarks

The performance of a hollow cathode discharge CW He–Cd$^+$ laser module capable of simultaneously delivering milliwatt output power at the three primary spectral lines blue, green and red was described in this paper. In particular, the laser output characteristics for single- and multi-line operation at λ = 441.6 nm, λ = 533.7 nm, λ = 537.8 nm, λ = 635.5 and 636.0 nm, and λ = 723.8 and 728.4 nm, and the power interactions between some of these lines, were presented.

The results obtained show that the most effective single-line laser oscillation in the red occurs at low He pressures (optimum 8 mbar), low Cd vapour pressures (optimum around 0.01 mbar) and relatively low total discharge currents (optimum 240 mA). The single-line oscillation in the blue is favoured by lower He pressures (optimum 8 mbar), relatively higher Cd vapour pressures (optimum around 0.026 mbar) and higher total discharge currents (400 mA and more). The optimum conditions for the single-line oscillation in the green are determined by relatively high He pressures (optimum 40 mbar), Cd vapour pressure higher than 0.02 mbar, and relatively high total discharge currents (400 mA and more). The laser resonator powers at the green and blue lines exhibit two optimum He pressures, 8 and 40 mbar for the two green lines, and 8 mbar and 27 mbar for the blue line. The most efficient simultaneous laser oscillations at the red, green, and blue lines in the low-He-pressure region occur for the same He pressure (8 mbar) as that at which the hollow cathode effects are strongest.

We confirmed the contribution of the radiative cascade transition of the red lines to excitation of the green lines, the output powers of which increase when the red lines oscillate simultaneously with them. Moreover, we find, to our knowledge for the first time experimentally, that the red lines also gain in their output power under simultaneous operation with the green lines, which de-populate the lower lasing levels of the red transitions. This power influence of the green lines on the red lines is strong, and under some conditions the de-population of the lower laser levels of the red transitions by the green lines' oscillations can be the dominant mechanism of build-up of the population inversion between the upper and lower levels of the red transitions.

The strong coupling between the red and green lines complicates intra-resonator modulation (with selective electro- or acusto-optic modulators, for example) of the individual laser lines. Such a modulation has been foreseen for the purpose of full-colour printing with a multicolour He–Cd$^+$ laser.

In contrast to the result of Kawase (1979), we did not find any power influence of the blue line on the other lines, nor vice versa. This discrepancy with the results of Kawase might result from much lower intra-resonator laser power in our case, and thus lower interaction between the laser lines. In our case, under the optimum conditions for multi-line operation (He pressure 8 mbar, Cd vapour pressure 0.01 mbar and total discharge current 260 mA), the intra-resonator powers for the 441.6, 533.7, 537.8 and both 635.5 and 636.0 nm lines, measured with the intra-resonator computerized assembly, were 500, 90, 200 and 135 mW, respectively. In the case of Kawase the corresponding intra-resonator laser powers, estimated from the laser output powers and the mirror transmittances given in the paper of Kawase (1979), were about 2120, 600, 650 and 145 mW at 635.5 nm and 715 mW at 636.0 nm. The influence of the blue line on the green and red lines inferred by Kawase on the basis of a bending phenomenon for the green and red lines when changing discharge current cannot be supported by our results, although a similar bending phenomenon was observed in our experiment (figure 12). We would attribute the bending phenomenon to the current saturation of the laser power of the red lines rather than to an increase in the laser power in the blue (figure 14, the curve for 7.5 mbar He pressure), as proposed by Kawase (1979). According to Green *et al* (1973), Latush *et al* (1973) and Green and Webb (1975), an increase in the discharge current in He–Cd discharges results in an increased number of slow electrons, which via superelastic collisions with Cd$^+$ ions in the upper laser states of both red laser transitions decrease their number, causing saturation and then eventually a decrease in the laser power in the red. Since, as shown by Kawase and us, the laser power in the green follows that in the red, the bending phenomenon is also observed for the green lines when changing discharge current. In summary, in our opinion the results of this experiment do not confirm coupling between the blue line and the green and red lines, and some further experiments are needed to elucidate this problem. During the procedure of publishing this paper we found a slight influence of the green line on the blue line (but not vice versa) in a CCRF-excited He–Cd$^+$ laser (Reich *et al* 1994). An experimental confirmation of the reinforcement of the red lines by the green lines when simultaneous oscillating was obtained also in the CCRF-excited He–Cd$^+$ laser.

The characteristics of the output power of the He–Cd^+ laser lines obtained in this investigation may be useful for further development of HCD and radio-frequency excited (Reich *et al* 1993, 1994) He–Cd^+ laser systems.

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