Comparison of He–Cd$^+$ White-Light Laser Oscillations in Longitudinal and Transverse Hollow-Cathode Tubes

J. MIZERACZYK, M. NEIGER, AND J. STEFFEN

Abstract—The results of a direct comparison of laser oscillations in two different hollow-cathode discharges, i.e., longitudinal and transverse, used for exciting the blue (441.6 nm), green (533.7 nm and 537.8 nm), and red (636.0 nm) lines of the Cd$^+$-ion in an He-Cd mixture are presented. The design of the discharge tube, which allows a direct comparison of the laser properties of both discharges in the same hollow-cathode segments and laser cavity is shown. The results showed the superiority of the longitudinal hollow-cathode discharge in generating the blue, green, and red lines simultaneously. The transverse hollow-cathode discharge more efficiently generates the green lines if the other laser lines are absent. This suggests the application of the longitudinal hollow-cathode discharge for white-light He-Cd$^+$ lasers.

I. Introduction

The hollow-cathode discharge (HCD) He-Cd$^+$ laser operating at the red (635. 5 and 636.0 nm), green (533.7 and 537.8 nm), and blue (441.6 nm) transitions of the Cd$^+$-ion has been the object of several investigations due to its ability to generate efficient white-light oscillation in a single laser tube.

Simultaneous three-color laser operation at red, green, and blue transitions in a He-Cd mixture in hollow-cathode systems was reported by Wang and Siegman [1] as early as 1973. A stable CW single-tube He-Cd$^+$ white-light laser of the HCD-type with good white light characteristics was demonstrated by Fujii *et al.* [2] in 1975. Further investigations have resulted in new design concepts of the white-light laser [3]-[9] and an approach to clarify the excitation mechanisms in such a laser [10], [11].

The presently known designs of the HCD He-Cd$^+$ white-light laser may be divided into two basic groups, depending on the position of the anodes and the cathodes relative to each other. To the first group belong those HCD tubes in which the configuration of the electrodes establishes an electric field along the axis of the cathode segment. Due to this axial (longitudinal) electric field the electrons are transported along the cathode segment towards the anode [Fig. 1(a)]. This kind of discharge is therefore called a *longitudinal HCD*.

Such a longitudinal HCD has been employed for white-light He-Cd$^+$ lasers presented in [1]-[7], [10], and [11]. In the second group of HCD tubes [Fig. 1(b)] the electrode configuration creates an electric field and a discharge current transversely to the axis of the hollow-cathode segment. As a result, a so-called *transverse HCD* occurs. Characteristics for the transverse HCD are homogeneity of the discharge plasma along the cathode, and the absence of an axial electric field. The transverse HCD has been employed in the white-light He-Cd$^+$ laser devices reported in [8] and [9].

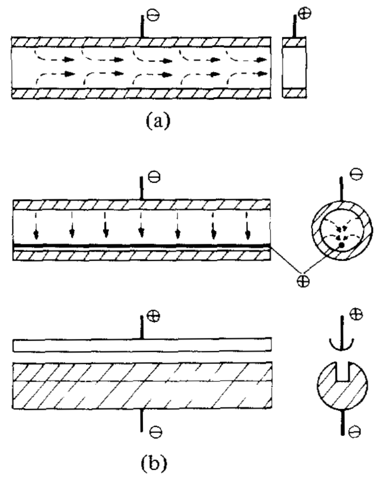

Fig. 1. Illustration of (a) longitudinal and (b) transverse (inner-anode and slotted type) HCD.

Due to the different geometrical electrode configurations, the discharge parameters and the laser excitation efficiency differ in longitudinal and transverse HCD's [12]. The applicability of both types of HCD discharges for laser excitation has been tested many times separately for each discharge. The only direct comparison, however, of the properties of both discharges has been carried out for an He-Kr$^+$ laser and showed some advantages of the transverse HCD for lasing at 469.4 nm [13]. However, these results are not necessarily applicable for the He-Cd$^+$ white-light laser.

This letter reports results of a direct comparison of laser properties for the two basic HCD's, i.e., longitudinal and transverse, used to excite red, green, and blue lines of the Cd$^+$-ions in an He-Cd mixture in both the same tube and the same laser cavity.

II. Experiment

The design of the laser discharge tube, similar to that in [13] is shown in Fig. 2. The tube consisted of two sets of four cylindrical stainless steel cathodes, each 9 cm long and 5 mm in internal diameter. Cathode segments of this length are

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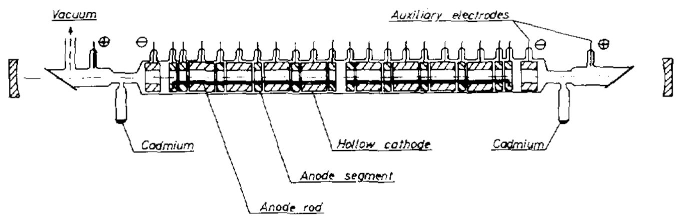

Fig. 2. Tube structure of He–Cd$^+$ laser with longitudinal and transverse HCD.

commonly used in HCD-laser technology and assure that both the longitudinal and transverse discharges could be stably operated in our device. Two types of anodes were used. Anodes of the first type were short cylindrical bore segments of 1 cm length and 5 mm in internal diameter each placed between the cathode segments. These were the anodes for the longitudinal HCD. The anodes for the transverse HCD discharge consisted of a 0.5 mm in diameter tungsten rod located parallel to the cathode axis at a distance of 0.5 mm from the inner cathode surface. In this case the former anode cylindrical segments were kept at floating potential. Similarly, the anode rod was floating during the longitudinal mode of operation.

These design features of the discharge tube allowed an easy choice of the mode of operation, longitudinal or transverse, in identical cathode segments, and, as a consequence, made possible a direct comparison of the laser properties of both discharges in the same laser cavity. Cadmium was supplied to the HCD by cataphoresis from two heated side-arms placed at each end of the tube. For this purpose two positive-column discharges at both ends of the tube were used. They also confined the cadmium vapor inside the cathode segment region. The pressure of cadmium vapor inside the cathode segment region was controlled by changing the temperature of the active part of the tube, which was contained in an oven. Half-wave rectified 50 Hz ac was used to excite the discharges.

The anode–cathode geometries presented above have properties typical of "pure" longitudinal and "pure" transverse discharges, respectively. However, among the hollow-cathode tube configurations known in literature, there are examples where the HCD-discharges cannot be classified as purely longitudinal or transverse. For example, seemingly longitudinal configurations with short cathode segments have plasma characteristics similar to those of transverse discharges. Therefore, our study presents the first comparison of He–Cd$^+$ laser properties with "pure" longitudinal or transverse discharges.

III. Results

The laser characteristics reported below are classified according to single-line or simultaneous multiline modes of operation of the laser.

A. Single-Line Operation

In the case of single-line operation, the He–Cd$^+$ laser output powers obtained with the longitudinal HCD at 441.6 nm and 636.0 nm were higher than with the transverse HCD. On the other hand, the laser power at 533.7 nm and 537.8 nm was always higher for the transverse HCD (Fig. 3).

The maximum output power at 636.0 nm was obtained at a helium pressure of about 8 mbar. Laser action for this line ceased at about 20 mbar and 18 mbar, respectively, for the

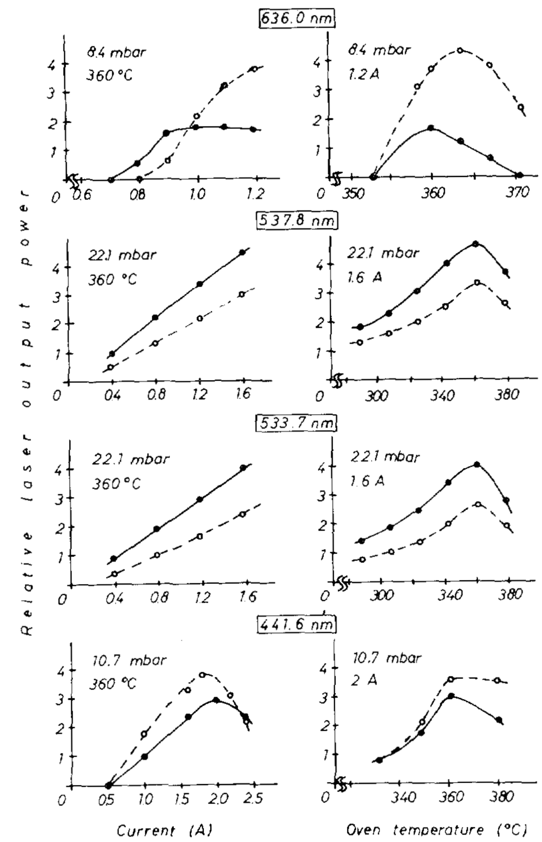

Fig. 3. The dependence of He–Cd$^+$ laser power on the discharge current and oven temperature for the longitudinal (broken line) and transverse HCD. Single-line operation.

longitudinal and transverse HCD. For the longitudinal HCD the output power increased with the discharge current and then saturated. For the transverse HCD, after an initial increase and saturation, the output power decreased with the discharge current. The laser output power at 533.7 nm behaved similarly to that at 537.8 nm. Both increased with the increase of helium pressure and became saturated at about 30 mbar for both discharges. Both lines increased with increasing current. The maximum output power for the 441.6 nm laser line occurred at the helium pressure of about 10 mbar. The lasing ceased at about 28 mbar and 18 mbar, respectively, for the longitudinal and transverse HCD. The laser power at 441.6 nm increased approximately linearly with the increase of discharge current up to 2 A, and then decreased.

The above results are consistent with those presented by Csillag *et al.* [8] for the transverse discharge, and with Kawase [5] for the longitudinal one. No distinct difference between the optimum Cd-vapor pressure (corresponding to the temperature of the oven) was observed for both discharges at the pressure optimum for the single-line operation. However, such a difference seems to exist for the 636.0 nm laser line.

B. Multiline Operation

The best simultaneous oscillation of red, green, and blue lines occurred at a helium pressure from 12 to 16 mbar. In this case (Fig. 4) the dependence of laser output power on the discharge mode differed from that for single-line operation. The three lines, 441.6, 537.8, and 636.0 nm were each stronger for the longitudinal HCD. Only the laser output power at 533.7 nm was higher with the transverse HCD than with the longitudinal

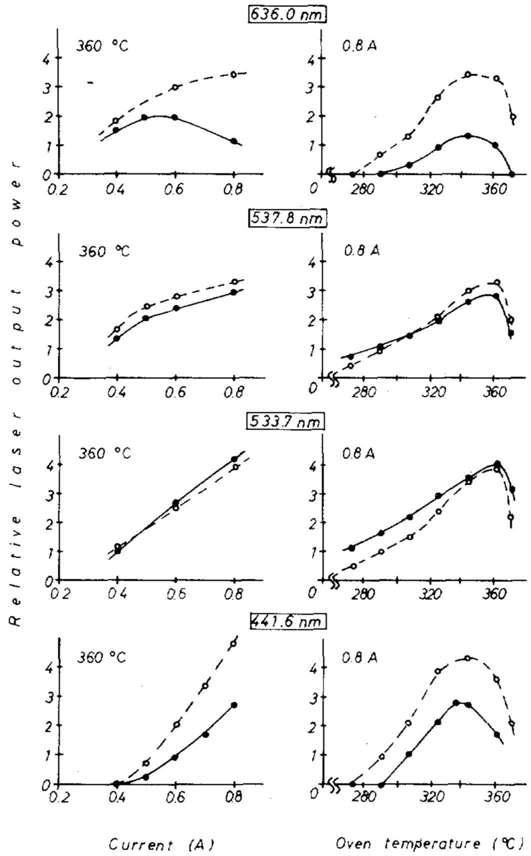

Fig. 4. The dependence of He–Cd$^+$ laser power on the discharge current and oven temperature for the longitudinal (broken line) and transverse HCD. Simultaneous multiline operation. Helium pressure 16, 4 mbar.

one, but this difference was smaller than that for single-line operation.

The variation of the laser output with helium and cadmium vapor pressures and discharge current was similar to that found for single-line operation, except for the 537.8 nm line. In case of multiline operation of the longitudinal HCD, the variation of the laser output power at 537.8 nm seems to follow the variation of the laser output at 636.0 nm. This can be understood assuming that that the green 537.8 nm transition is excited considerably by charge transfer from He$^+$ ions [14], followed by a cascade process to the upper green laser level through the red (636.0 nm) laser transition. This contribution of cascade pumping to the total pumping mechanisms of the green lines has been reported earlier by Kawase [5]. The enhancement of laser output at 533.7 nm for multiline operation seems to be weaker than that at 537. 8 nm and could hardly be observed in our experiment.

IV. Conclusions

Our results show the superiority of a purely longitudinal HCD for simultaneously generating red, green, and blue He–Cd$^+$ laser light. The laser output power is higher than that with a purely transverse one. The range of variation of operating parameters (helium and cadmium-vapor pressures, discharge current) is wider in the case of the longitudinal HCD. Therefore, the longitudinal HCD is recommended as an excitation source for white-light He-Cd$^+$ lasers, while a transverse HCD, technically simpler to realize, is more suitable for generating the green laser lines.

Our measurements confirmed the importance of cascade pumping of the 537.8 nm laser line by the 636.0 nm laser line.

The reason for the superiority of the longitudinal discharge for the excitation of white-light He-Cd$^+$ lasers is not clear. However, a difference in the electron energy distribution functions of both discharges might be responsible for that.

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References

[1] S. C. Wang and A. E. Siegman, "Hollow-cathode transverse discharge He–Ne and He–Cd$^+$ lasers," *Appl. Phys.*, vol. 2, pp. 143–150, 1973.
[2] K. Fujii, T. Takahashi and Y. Asami, "Hollow-cathode-type CW white light laser," *IEEE J. Quantum Electron.*, vol. QE-11, pp. 111–114, 1975.
[3] S. Fukuda and M. Miya, "A metal-ceramic He–Cd II laser with sectioned hollow cathodes and output power characteristics of simultaneous oscillations," *Japan. J. Appl. Phys.*, vol. 13, pp. 667–674, 1974.
[4] K. Fujii, S. Miyazawa, T. Takahashi, and Y. Asami, "Design of white laser based on cathode fall theory," *IEEE J. Quantum Electron.*, vol. QE-15, pp. 35–44, 1979.
[5] H. Kawase, "Power interaction of laser lines in He–Cd II white color oscillation," *Japan. J. Appl. Phys.*, vol. 18, pp. 2111–2119, 1979.
[6] K. Fujii, T. Oshima, M. Otaka, S. Nagashima, S. Miyazawa, and T. Oikawa, "A new design concept for hollow-cathode white light laser," *IEEE J. Quantum Electron.*, vol. QE-16, pp. 590–592, 1980.
[7] M. Otaka, T. Shima, M. Takeuchi, T. Oikawa, and K. Fujii, "He–Cd$^+$ white light laser by a novel tube structure," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 414–417, 1981.
[8] L. Csillag, C. Z. Nam, M. Janossy, and K. Rozsa, "Output characteristics of a hollow cathode He–Cd laser," *Opt. Commun.*, vol. 21, pp. 39–41, 1977.
[9] J. Mizeraczyk, J. Konieczka, J. Wasilewski, and K. Rozsa, "High-voltage hollow-cathode He–Cd$^+$ laser," in *Proc. Int. Conf. Lasers '80*, New Orleans, LA, 1981, pp. 177–181.
[10] K. H. Wong and C. Grey Morgan, "White light laser," *J. Phys. D: Appl. Phys.*, vol. 16, pp. L1–L4, 1983.
[11] ——, "Population inversion mechanisms in He–Cd$^+$ hollow cathode lasers," in *Proc. 16th Int. Conf. Phenom Ionized Gases*, vol. II, Düsseldorf, W. Germany, 1983, pp. 216–217.
[12] J. Mizeraczyk: "Investigations of longitudinal hollow-cathode discharge," *Acta Physica Hungarica*, vol. 54, pp. 71–95, 1983.
[13] J. Mizeraczyk, J. Wasilewski, J. Konieczka, W. Urbanik, M. Grozeva, and J. Pavlik, "Comparsion of He–Kr$^+$ laser oscillations in transverse and longitudinal hollow-cathode discharges," in *Proc. Int. Conf. Lasers '81*, New Orleans, LA, 1982, pp. 877–881.
[14] G. J. Collins, R. C. Jensen and W. R. Bennett, "Charge-exchange excitation in the He–Cd laser," *Appl. Phys. Lett.*, vol. 19, pp. 125–128, 1971.