Absorption of the 441.6 nm He-Cd$^+$ laser line in a He-Cd positive column utilized in cataphoretic confinement

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The experimental investigation showed that the absorption of the 441.6 nm He-Cd$^+$ laser line by the He-Cd positive column in the cataphoretic confinement sections used in hollow-cathode discharge He-Cd$^+$ lasers is relatively low ($\sim$0.1% per a few-cm-long He-Cd positive column). Such a low absorption should not decrease the 441.6 nm output power of the hollow-cathode discharge He-Cd$^+$ lasers more than a few percent. Estimates show that the Cd_2^* molecules may be responsible for this absorption.

I. INTRODUCTION

The confinement of Cd vapor to the excitation section of the discharge tube is a current technology problem of hollow-cathode discharge (HCD) He-Cd$^+$ lasers which belong to a laser group generating the so-called white-light laser beams, i.e., consisting of the three fundamental spectral lines: blue, green, and red, emitted simultaneously (Fujii, Takahashi, and Asami[1]). In the case of the HCD He-Cd$^+$ lasers these lines are 441.6, 533.7, 537.8, 635.5, and 636.0 nm. The way of realizing the Cd vapor confinement in the HCD He-Cd$^+$ lasers, originally introduced by Hernquist[2,3] for positive column (PC) He-Cd$^+$ lasers, is schematically shown in Fig. 1. In the method presented in Fig. 1 the confinement of Cd vapor to the laser excitation section is due to cataphoretic action (Laška[4] and Chanin[5]) occurring in the so-called PC confinement sections. Although there exists a controversy regarding the efficiency of the Cd particles' cataphoretic confinement to the laser excitation section, the cataphoretic confinement, even if not perfect, is experimentally proved as very effective (Mizeraczyk, Carlsson, and Hård[6]).

However, the cataphoretic confinement sections on the axis of the HCD He-Cd$^+$ lasers may contribute to absorptions of the generated laser lines and thus influence the output powers of the lasers. It appears that the positive column built up in the cataphoretic confinement section is divided into three parts (Mizeraczyk, Carlsson, and Hård[6]): (i) the Cd-like discharge region, located near the excitation section, in which the Cd atom density decreases linearly from the excitation section towards the anode; (ii) the transition region, in which the Cd atom density decreases quasiexponentially; (iii) and the He-like discharge region, adjacent to the anode, which seems to be free from Cd atoms.

A side-light observation of the Cd-like discharge region showed that this part of the confinement section emits broad spectral bands (Fig. 2), presumably due to the presence of molecular Cd particles (Cd_2, Cd_3, and Cd_2^+). The presence of the molecular Cd particles is highly probable in the Cd-like discharge region of the cataphoretic confinement section because of a relatively high density of Cd atoms ($\sim 10^{15}$ cm^{-3}, which is much higher than the Cd density typical of the PC He-Cd$^+$ lasers, being equal to about 1.5×10^{13} cm^{-3}). In the case of Cd_2 molecules, strong broadband absorptions between the $^3\Pi_g$ metastable state and the bound $^3\Pi_u$ charge-transfer state, as well as weaker but still significant broadband absorptions between the $^3\Sigma_u^+$ state and the repulsive $^3\Sigma_g^+$ state are predicted in the vicinity of 470 nm (Stevens[7]). Therefore, the absorption of the 441.6 nm He-Cd$^+$ laser line may be expected in the cataphoretic confinement sections.

In this article an experimental investigation of the absorption of the 441.6 nm He-Cd$^+$ laser line by the He-Cd positive columns built up in the cataphoretic confinement sections used in the HCD He-Cd$^+$ lasers is presented.

II. EXPERIMENT

A schematic of the He-Cd discharge tube used as an absorption cell in this experiment is shown in Fig. 3. The tube consisted of the two anodes, the cathode, the two capillary PC sections located between each anode and the cathode, and a Cd source. Each of the capillary PC sections, in which the absorption was to be investigated, was made of an 11-cm-long fused silica tube with an inner diameter of 3 mm. The capillary PC tubes were separated from each other by a distance of 3 mm, which enabled Cd vapor to enter into both capillary positive columns. The capillary PC sections were placed in a fused silica cylinder so that Cd vapor could reach the anode parts of the discharge tube only through both capillaries. The discharge tube was terminated with quartz Brewster windows fused to the tube endings.

Separate ovens were provided for the cathode, the Cd source and the capillary PC sections so that their temperatures could be controlled independently. The temperatures of the cathode and capillary PC sections were always kept at 663 K, which was well above the Cd source temperature. This prevented condensation of Cd atoms outside the Cd source.

The discharge tube and its parts were highly cleaned before using them in the experiment. Prior to placing the

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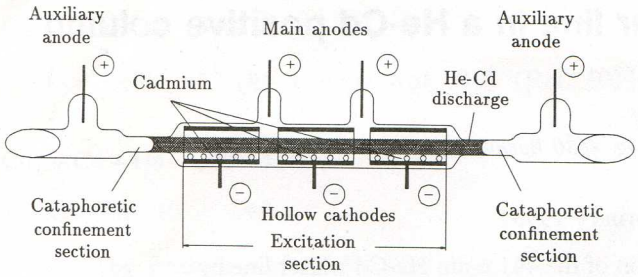

FIG. 1. Schematic of a HCD He-Cd$^+$ laser tube showing the cataphoretic confinement sections which prevent diffusion of Cd particles out of the excitation region.

Cd pieces into the Cd source they were distilled in vacuum. The tube was cleaned by pumping, baking (all parts of the tube except the Cd source up to 693 K) and running the discharge during several days. In the measurement highly pure helium (0.999 996) was used.

Comparing the absorption tube (Fig. 3) with the HCD He-Cd$^+$ laser tube presented in Fig. 1 shows that the capillary PC sections of the former tube play the role of the cataphoretic confinement sections. After vaporizing cadmium in the Cd source of the absorption tube, the Cd particles diffuse into the capillary PC sections towards the anodes. However, the Cd ions drift, oppositely directed due to cataphoresis, counteracts the Cd particles diffusion, eventually establishing an equilibrium typical of the cataphoretic confinement section, i.e., dividing the positive column of the confinement section into the Cd-like discharge region, the He-like discharge region, and the transition region between them. An example of such an equilibrium is schematically shown for a fixed temperature of the Cd source in Fig. 3. The length of the Cd-like discharge region can be varied (at the expense or in favor of the He-like discharge region) by varying the Cd source temperature. Since the relation between the length of the Cd-like discharge region and the total number of Cd atoms in this region is known (Mizeraczyk, Carlsson, and Hård[6]), the dependences of the 441.6 nm He-Cd$^+$ laser line absorption on the Cd-like discharge region length as well as on the total Cd atom number present in this region could be found in this experiment.

FIG. 3. Schematic of a discharge tube for absorption measurement in the He-Cd positive column of the cataphoretic confinement section.

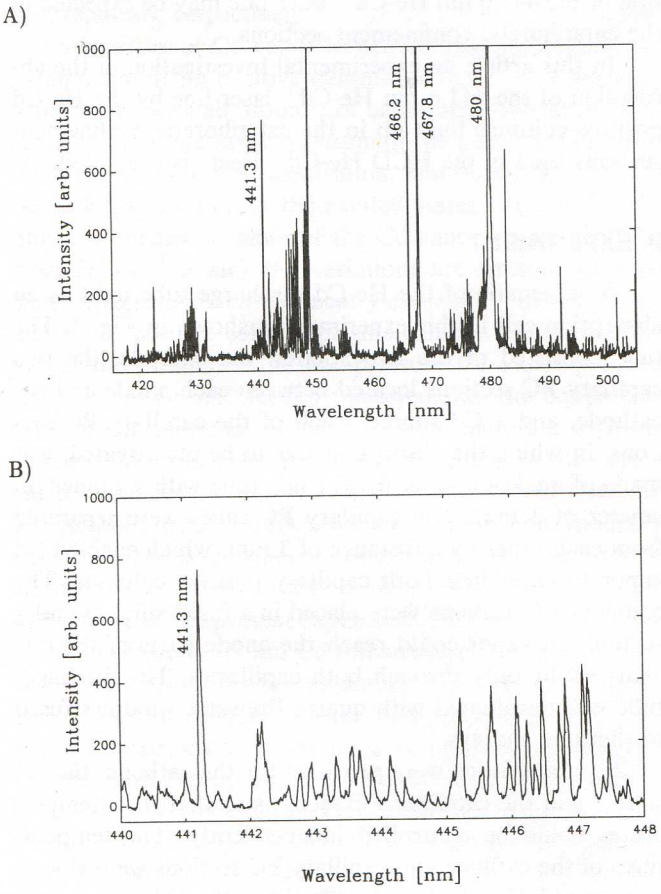

FIG. 2. (a) Optical multichannel analyzer traces of the molecular band groups in the emission spectrum for the He-Cd positive column of the cataphoretic confinement section as in Fig. 3. (b) A fragment of the emission spectrum in enlarged scale. The identified CdI lines are marked. CdII lines are too weak to be identified.

To carry out the measurement the absorption tube, a PC He-Cd$^+$ laser discharge tube and an assembly for measuring internal losses of a laser resonator were coaxially placed between two almost nontransmitting laser mirrors, thus forming a laser resonator. After initiating the laser generation at 441.6 nm relative changes of the laser power in the resonator were measured for various lengths of the Cd-like discharge region, i.e., $(P_0-P)/P_0$, where P_0 and P are the laser powers in the resonator without any Cd vapor in the absorption tube and for a given length of the Cd-like discharge region in it, respectively. Then, having the discharge in helium only and starting from the same laser power in the resonator P_0, similar changes of $(P_0-P)/P_0$ were produced by introducing known resonator internal losses as a result of revolving two plane-parallel plates of the assembly. By comparing both measurements the absorption of the 441.6 nm laser line as a function of Cd-like discharge region length could be found.

The discharge conditions were typical of the HCD He-Cd$^+$ lasers, i.e., the discharge current per one cataphoretic confinement section was up to 250 mA, the He pressure ranges from 4 to 16 mbar, the maximum Cd vapor pres-

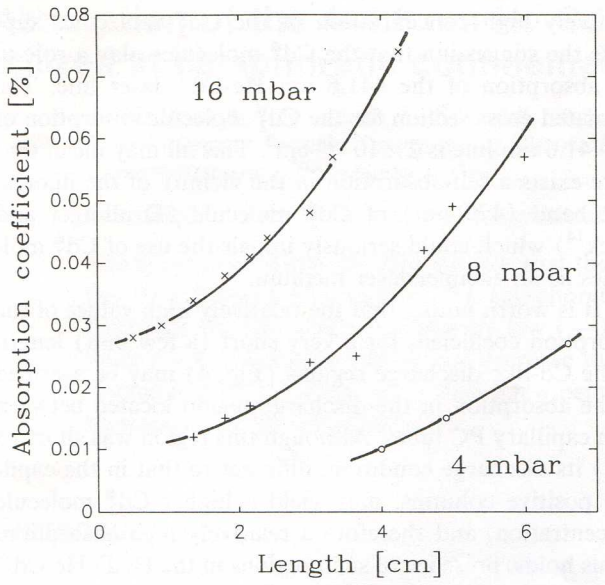

FIG. 4. The absorption coefficient of the 441.6 nm He-Cd$^+$ laser line as a function of Cd-like discharge region length in the cataphoretic confinement section. Discharge current in the section: 200 mA, He pressure (mbar): ○—4, +—8, ×—16.

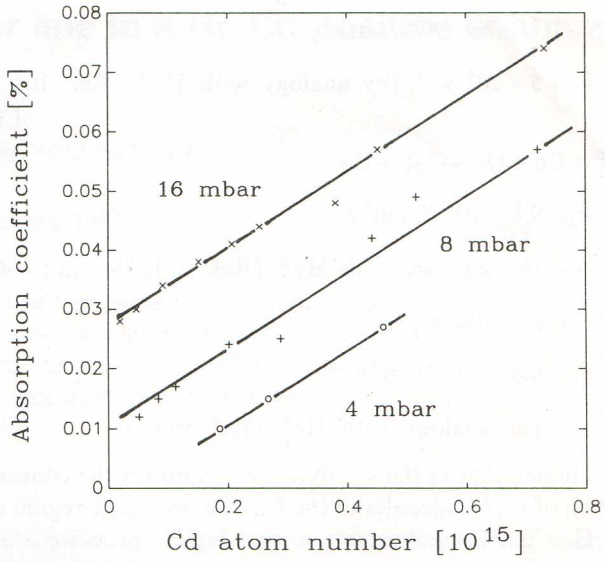

FIG. 5. The absorption coefficient of the 441.6 nm He-Cd$^+$ laser line as a function of the total Cd atom number (ΣN_{Cd}) in the Cd-like discharge region of the He-Cd positive column in the cataphoretic confinement section. Discharge current in the section: 200 mA, He pressure (mbar): ○—4, +—8, ×—16.

sure, corresponding to the Cd source temperature of 643 K, was about 0.6 mbar (Roth[8]).

III. RESULTS AND DISCUSSION

Typical results of the measurements of the absorption of the 441.6 nm He-Cd$^+$ laser line in the He-Cd PC of the cataphoretic confinement section as a function of length of the Cd-like discharge region are shown in Fig. 4. The results show that the absorption coefficient α of the 441.6 nm He-Cd$^+$ laser line [defined for a given length of the absorbing region as $\alpha=\ln(I_0/I)$ or $\alpha\sim(I_0-I)/I_0$ for $\alpha\ll1$, where I_0 and I are the intensities of radiation entering and leaving the absorption region, respectively] is, in general, low. The relative changes of the 441.6 nm He-Cd$^+$ laser power in the resonator $(P_0-P)/P_0$, measured in this experiment hardly exceeded 10%. However, one should take into account that a relatively high small signal gain at 441.6 nm of the PC He-Cd$^+$ laser tube used (around 7% for a single pass through the resonator) makes the laser power relatively insensitive to the actually low losses introduced by the cataphoretic confinement sections. On the other hand, the almost nontransmitting laser mirrors used in this experiment increases the laser power sensitivity to the introduced losses. Therefore, in a real HCD He-Cd$^+$ laser the relative laser output power drop at 441.6 nm due to the presence of the He-Cd positive columns in the cataphoretic confinement sections (usually not longer than 3 cm in the confinement section with a capillary of 3 mm i.d.) should be not higher than a few percent, if the small signal gain coefficient for the 441.6 nm laser line per single pass is higher than 5% and the outcoupling mirror transmission is around 1%, which is realistic.

It is seen from Fig. 4 that the absorption coefficient of the 441.6 nm laser line increases almost linearly with increasing He pressure at a fixed length of the Cd-like discharge region, and it increases approximately parabolically with increasing length of the Cd-like discharge region at a constant He pressure. Besides, the measurements also showed that the discharge current dependence of the absorption coefficient is similar to its dependence on He pressure, i.e., the absorption coefficient increases with increasing discharge current at a fixed length of the Cd-like discharge region. Such a behavior can be explained if one considers that the total number of Cd atoms in the Cd-like discharge region varies parabolically with increasing length of this region, and that at a fixed length of the Cd-like discharge region the total number of Cd atoms increases with increasing discharge current and He pressure (Mizeraczyk, Carlsson, and Hård[6]). The data presented in Ref. 6 enabled determining the dependence of the 441.6 nm laser line absorption coefficient on the total number of Cd atoms in the Cd-like discharge region. Figure 5 shows the result. It is seen that the absorption coefficient increases almost linearly with increasing the total number of Cd atoms in the Cd-like discharge region (ΣN_{Cd}) and also with increasing He pressure (p_{He}), i.e., $\alpha\sim p_{He}\times\Sigma N_{Cd}$. Estimates show that Cd_2^* molecules may be responsible for the absorption of the 441.6 nm laser line in the Cd-like discharge region. Assuming that the production and destruction of the Cd_2^* molecules in the Cd-like discharge region occur in the following processes:

$$Cd^*+Cd+He\rightarrow Cd_2^*+He,$$

$$k_1=3\times10^{-31}\ \text{cm}^6\,\text{s}^{-1}\ \text{(Ref. 9)}, \tag{1}$$

$$Cd^*+Cd+Cd\rightarrow Cd_2^*+Cd,$$

$$k_2=3\times10^{-32}\ \text{cm}^6\,\text{s}^{-1}\ \text{(Ref. 10)}, \tag{2}$$

$Cd_2^* \rightarrow 2Cd + h\nu$ (470 nm),

$k_3 = 5 \times 10^4$ s^{-1} [by analogy with Hg_2^* (Ref. 10)], (3)

$Cd_2^* + Cd + He \rightarrow Cd_3^* + He$,

$k_4 = 9.8 \times 10^{-31}$ cm^6 s^{-1}

[by analogy with Hg_2^* (Ref. 9)], (4)

$Cd_2^* + e \rightarrow$ products,

$k_5 = 6.8 \times 10^{-9}$ cm^3 s^{-1}

[by analogy with Hg_2^* (Ref. 9)], (5)

one obtains that in the steady-state conditions the concentration of Cd_2^* molecules in the Cd-like discharge region of the He-Cd PC confinement section [at He pressure ~ 10 mbar, Cd vapor pressure $\sim (10^{-2}$–$5 \times 10^{-1})$ mbar, discharge current ~ 150 mA, and electron concentration $N_e \sim 10^{13}$ cm^{-3}] is approximately given by

$$N_{Cd_2^*} \approx \frac{k_1 \times N_{Cd} \times N_{Cd^*} \times N_{He}}{k_3 + k_5 \times N_e}. \quad (6)$$

Here, N_{Cd} and N_{Cd^*} are concentrations of the Cd atoms in the ground state and the excited 5 ^3P states, respectively; $N_{Cd_2^*}$ and N_{He} are concentrations of the Cd_2^* molecules and the He atoms, respectively.

Admixture of Cd vapor to helium changes the plasma parameters of the positive column of the glow discharge. Addition of a small amount of cadmium (less than 10^{-2} mbar) results in a large variation of the axial electric field, electron energy and concentration, and populations of the He and Cd particles in the excited states (e.g., Ref. 11). But, at a further increase of the Cd vapor pressure (10^{-2} mbar-5×10^{-1} mbar) the variations are smaller and the plasma parameters remain nearly constant.[12] In this range the He-Cd positive column plasma exhibits properties typical of the plasma of the low-pressure Cd vapor positive column. Penkin and Redko[13] showed that the concentrations of Cd atoms in the 5 $^3P_{0,1,2}$ states saturate with increasing Cd vapor pressure in such a plasma. In the experiment described in Ref. 6 it has been observed that the intensity of the 326.1 nm Cd line originating from the 5 $^3P_1$ Cd level remains constant as the Cd vapor pressure is varied from 10^{-2} to 10^{-1} mbar in the He-Cd plasma similar to that used in the present experiment (in Ref. 6 the similar behavior of the 477.9 nm Cd line intensity is shown only). The above allows further assuming in Eq. (6) that N_{Cd^*} and N_e remain constant when N_{Cd} is varied from 10^{-2} to 5×10^{-1} mbar, which yields: $N_{Cd_2^*} \sim N_{He} \times N_{Cd}$. Comparing this with the experimental result that $\alpha \sim p_{He} \times \Sigma N_{Cd}$ (Fig. 5) may suggest the Cd_2^* molecules as a potential absorber of the 441.6 nm laser line. Moreover, an estimate done for $N_{He} = 2.65 \times 10^{17}$ cm^{-3} (corresponding to $p_{He} = 10$ mbar), $N_{Cd} = 7.48 \times 10^{15}$ cm^{-3} (corresponding to $p_{Cd} = 0.5$ mbar), $N_{Cd^*} = 5 \times 10^{12}$ cm^{-3} (Ref. 13), $N_e = 1 \times 10^{13}$ cm^{-3} (Ref. 11) gives $N_{Cd_2^*} \approx 2.5 \times 10^{10}$ cm^{-3}. Such a relatively high concentration of the Cd_2^* molecules supports the suggestion that the Cd_2^* molecules play a role in the absorption of the 441.6 nm He-Cd^+ laser line. The estimated cross section for the Cd_2^* molecule absorption of the 441.6 nm line is 2×10^{-14} cm^2. This all may mean that there exists a self-absorption in the vicinity of the fluorescent band (470 nm) of Cd_2^* molecule (Drullinger and Stock[14]) which could seriously impair the use of Cd_2^* molecules as an excimer laser medium.

It is worth noting that the relatively high values of the absorption coefficient for a very short (a few mm) length of the Cd-like discharge regions (Fig. 4) may be ascribed to the absorption in the discharge region located between both capillary PC tubes. Although this region was short (3 mm) its discharge condition, different to that in the capillary positive columns, may yield a higher Cd_2^* molecule concentration, and therefore a relatively high absorption. If this holds, presence of such regions in the HCD He-Cd^+ laser tubes would affect their output powers.

Summing up, the experimental investigation shows that the absorption of the 441.6 nm He-Cd^+ laser line by the He-Cd positive columns of the cataphoretic confinement sections as used in the HCD He-Cd^+ lasers is relatively low ($\alpha_{max} = 0.1\%$ per section) and it should not decrease the output powers of the lasers more than a few percent. From the reasoning presented above one may conclude that the Cd_2^* molecules are responsible for this absorption.

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