cw He-Kr$^+$ laser with transverse radio frequency excitation

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A cw He-Kr$^+$ laser was excited with a capacitively coupled transverse radio frequency discharge. The laser was operated in a simple 40-cm active length alumina oxide tube which ends off via ceramic glass transitions in Brewster windows. Transformation of the laser discharge tube impedance to the 50 Ω output resistance of the rf source and symmetrization of the rf voltage were performed by a special matching network. cw lasing was obtained at 469.4, 458.3, 438.7, and 431.8 nm. The output power of all lines amounts to 35 mW at an input power of 600 W. The rms noise of the laser intensity did not exceed 0.6%.

Due to fast electrons produced in the space charge layers in front of the radio frequency (rf electrodes,[1] the capability of the capacitively coupled transverse radio frequency (ccrf) discharge to generate laser oscillations has been believed to be similar to that of the hollow-cathode discharge (HCD).[2–5] This is confirmed by the generation of many laser lines of metal ions, provided by the HCDs, which have been also obtained using the ccrf excitation.[6–8] However, laser oscillations on rare-gas ion transitions, usually excited in the HCD[9] have not yet been reported as obtained with the ccrf discharge. Among others this concerns laser oscillations on the Kr II transitions, which up to now have been only obtained in different cw and pulsed HCDs[10–18] and in a pulsed positive column discharge.[19]

In this letter we report cw laser oscillations at the 431.8- , 438.7- , 458.3- , and 469.4-nm lines of Kr II excited by a ccrf discharge in He-Kr mixtures. These lines are presumably excited by collisions of the second kind between metastable He atoms and ground state Kr ions,[19] the number densities of which depend on the number of fast electrons. Our investigation on the ccrf-excited He-Kr$^+$ laser also showed that typical problems of the HCD-excited laser, such as arcing, sputtering of the electrode material, nonuniformity of the discharge column, and the gas component separation due to cataphoresis may be avoided, at least partially, using ccrf discharge excitation instead.

The laser tube used in our experiment is characterized by a very simple design. The 400-mm-long active part of the laser tube with an outer and inner diameter of 7 mm and 2.8 mm, respectively, was made of ceramic alumina oxide. The tube ends were connected using ceramic glass transitions with fused silica end pieces on which fused silica Brewster windows were soldered. The rf power was capacitively coupled into the discharge with 400-mm-long and 3-mm-wide transverse nickel plated copper electrodes mounted at the tube with ceramic holders. Using copper as electrode material a homogeneous heat distribution was achieved along the tube whereas by the nickel plating the oxidation of the electrode was avoided. The discharge was maintained by a rf generator operating at 13.56 MHz with an output power up to 600 W.

A special matching network was developed to transform the laser discharge tube impedance Z_D of approximately $(20 - j230)\ \Omega$ at an input power $P_{\text{rf}}=600$ W to the 50-Ω output resistance of the rf source. Z_D was determined from measuring the current and voltage amplitude and the real power input to the tube. The matching network symmetrizes the rf voltage to obtain a uniform discharge between the two electrodes. Thus problems occurring with a nonsymmetrized rf voltage, as spreading of the discharge beyond the electrode gap and strong rf interference were avoided by the symmetric matching.

It should be mentioned that in a tube made solely of fused silica the laser action ceased within a few minutes after ignition of the discharge. It was presumably due to contamination of the laser by fused silica sputtered from the wall by ion bombardment. The ion-caused sputtering of fused silica is relatively high. For example, the Ar$^+$ ion-caused sputtering of fused silica is by a factor of 7.5 higher than that of Al_2O_3.[20] If an Al_2O_3 tube was inserted into the fused silica tube permanent laser action could be achieved, however, the output power was distinctly lower than that of the bare Al_2O_3 tube. This may be caused by higher and locally varying dielectric losses in the Al_2O_3 tube due to a higher and inhomogeneous tube temperature. Moreover parasitic discharges between the outer wall of the Al_2O_3 tube and the inner wall of the fused silica tube appear at higher input power.

The Al_2O_3 tube was filled with a mixture of He and Kr, the He:Kr ratio was 1500:1, which was close to the optimum. The He pressure range for maximum laser output power for all four lines was 13.0 kPa±0.3 kPa laser action at 469.4 nm could be achieved in a pressure range of 2.5 to 26 kPa.

A laser resonator was formed by two highly reflecting mirrors with a radius of curvature of 1 m. The laser was tuned to oscillate separately on the different lines with a birefringent filter.[21] A symmetric pair of fused silica plates with Brewster window quality was used to insert variable losses into the resonator. With a fixed third plate a small constant fraction of the resonator power was decoupled from the resonator and measured as a function of the variable losses.[22,23] To eliminate a source of systematic error a polarizer transmitting only light polarized parallel to the plane of incidence of the laser beam onto the plate was placed in front of the measuring diode. Taking into account the output cou-

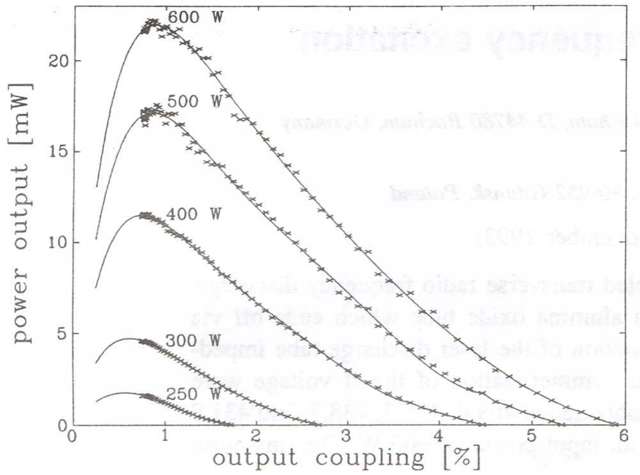

FIG. 1. Laser power output vs output coupling for the 469.4-nm Kr$^+$ line with rf power P_{rf} as a parameter.

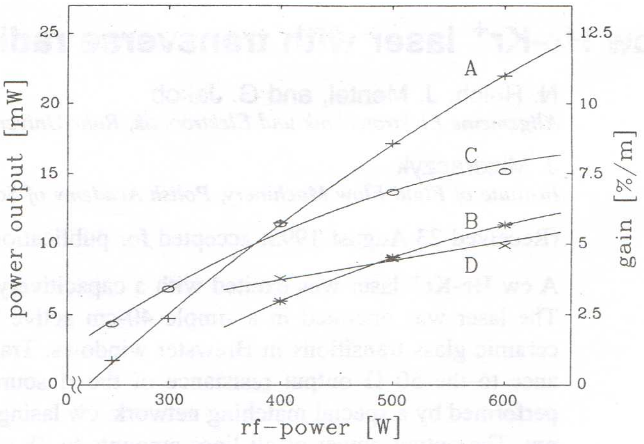

FIG. 3. Maximum laser power output P_L of the 469.4-nm line (A) and the 431.8-nm-line (B) and small signal gain g_{max} of the 469.4-nm (C) and the 431.8-nm line (D) in dependence on rf power P_{rf}.

pling of the two rotating and the fixed plate, of the birefringent filter and of the laser mirrors the total output coupling from the resonator was calculated. The laser power output versus output coupling was determined from the product of the measured resonator power and the total output coupling. It is presented with the input power P_{rf} as a parameter in Figs. 1 and 2 for the 469.4-nm line and the 431.8-nm line, respectively. The left-hand side of the curves showing no measuring points was obtained from extrapolation of the measured resonator power.

The small signal gain per meter g_{max} and the maximum power output P_L of the 469.4-nm and the 431.8-nm line taken from Figs. 1 and 2 are presented as a function of P_{rf} in Fig. 3. With $P_{rf}=600$ W maximum output powers of 22 mW at 469.4 nm and 11 mW at 431.8 nm were obtained. The corresponding values for the 438.7-nm line were $g_{max}=1.8\%/m$ and $P_L=1.6$ mW at $P_{rf}=600$ W. The 458.3-nm line barely exceeded threshold at $P_{rf}=600$ W ($g_{max}=0.5\%/m$). As is seen from Fig. 3 a saturation of the laser power output with increasing P_{rf} up to 600 W was not found, so an increase of the laser power can be expected at higher input power. Moreover, an optimization of the diameter and design of the tube, and the He:Kr ratio has not been finished yet. A much lower power output achieved with a tube of 4.9-mm inner diameter has already shown that a small tube diameter is favorable for a high laser power output. The reason may be that the relatively low gain of the laser increases when the tube diameter *d* is reduced while the product *pd* is kept constant.

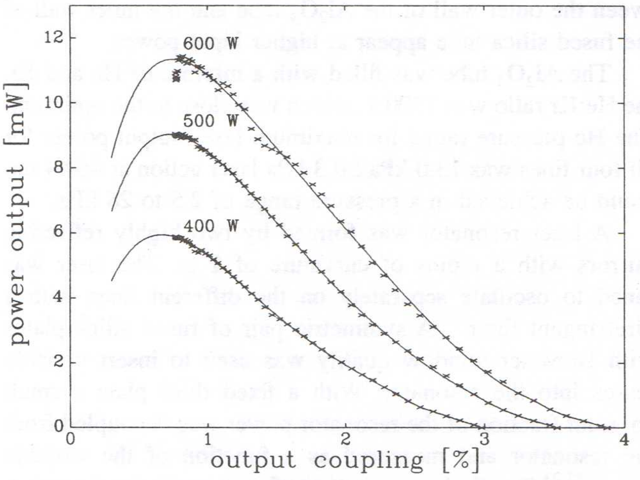

FIG. 2. Laser power output vs output coupling for the 431.8-nm Kr$^+$ line with P_{rf} as a parameter.

For the noise measurements a 2-m out coupling mirror was used. The laser output power was detected with a *p-i-n* photodiode. Since the main part of the laser noise occurs at low frequencies the noise spectrum was recorded with a spectrum analyzer (FSBS, Rohde & Schwarz) in a frequency range from 70 Hz to 1.5 MHz. The noise power of the laser was evaluated from these measurements and divided by the average power of the laser. The rms noise did not exceed 0.6%. This value agrees with the ratio which was indicated by a digital oscilloscope (9450, LeCroy) fed by the photodiode signal. For comparison the noise of a He-Cd$^+$ laser excited with a positive column amounts to several percent.[24] The measurements given above were performed after 500-h operation of the laser tube.

We presented a new cw He-Kr$^+$ laser with capacitively coupled transverse radio frequency excitation. Laser action on four blue-violet lines of the krypton ion was achieved in a laser tube of very simple design. The operation of the cw He-Kr$^+$ laser with ccrf excitation confirms that the properties of hollow cathode discharges and ccrf discharges must be similar, i.e., in both discharges electrons with energy high enough to excite high lying levels are present.

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