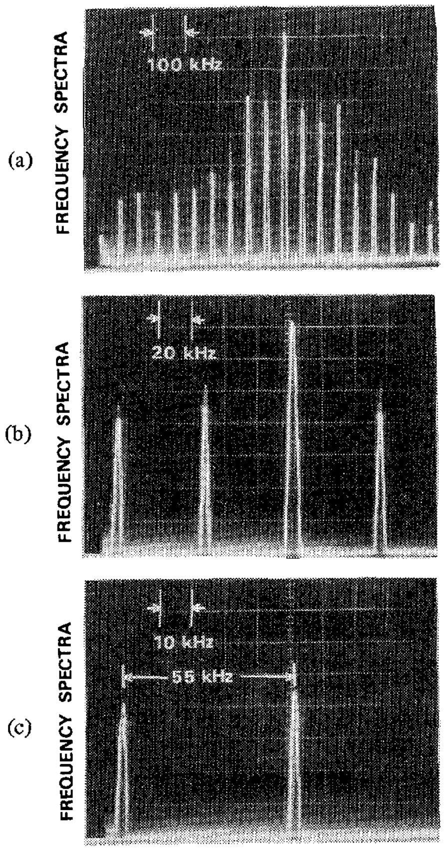

Fig. 3. The fine structure of the self-sustained oscillation spectrum. The frequency spectrum shown in trace (a) is further resolved in traces (b) and (c).

fier and a step-index multimode fiber, was investigated. As a result, it is found that the spectral profile of the self-sustained oscillation follows the baseband frequency response of the fiber. If the nonlinear phenomenon in the oscillator is vanishingly small over wide oscillation frequency range, we may obtain the frequency characteristics of the wideband fiber such as graded-index multimode fibers. In addition, applying a mode-locking technique for the self-sustained oscillator, we could measure the frequency response of the system more precisely.

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REFERENCES

[1] M. Nakazawa, M. Tokuda, and N. Uchida, "Self-sustained intensity oscillation of a laser diode introduced by a delayed electrical feedback using an optical fiber and an electrical amplifier," *Appl. Phys. Lett.*, vol. 39, pp. 379–381, 1981.
[2] W. J. Cunningham, "Nonlinear oscillators with constant time delay," *J. Franklin Inst.*, vol. 261, pp. 495–507, 1956.
[3] V. Met, "On multimode oscillators with constant time delay," *Proc. IRE*, vol. 45, pp. 1119–1128, 1957.
[4] M. I. Disman and W. A. Edson, "Simultaneous asynchronous oscillations in class-C oscillators," *Proc. IRE*, vol. 46, pp. 895–903, 1958.
[5] I. Kobayashi and M. Koyama, "Measurement of optical fiber transfer function based upon the swept frequency technique for baseband signal," *IECE Japan*, vol. E59, pp. 11–12, 1976.

Zn II and As II CW Laser Transitions Excited by an Electron Beam

J. J. ROCCA, J. D. MEYER, AND G. J. COLLINS

***Abstract*—CW laser action was obtained on the 4911.6, 4924.0, 6102.5, and 7588.5 Å transitions of Zn II and on the 6511.7 Å transition of As II using electron beam excitation of He-Zn and He-As mixtures, respectively.**

INTRODUCTION

RECENTLY, we demonstrated the use of dc electron beams to excite CW ion lasers, obtaining CW laser action in singly ionized mercury [1], iodine [2], and selenium [3]. Electron beam created plasmas provide a non-Maxwellian electron energy distribution, with a high density of energetic electrons, which makes them an attractive medium for ion lasers. We now report CW laser oscillation in singly ionized zinc and arsenic using this same electron beam pumping scheme to excite He-Zn and He-As mixtures. CW laser radiation was achieved on the 4911.6, 4924.0, 6102.5, and 7588.5 Å transitions of Zn II and on the 6511.7 Å transition of As II.

The laser setup used was similar to that employed previously [1]-[3]. The electron beam is injected into a plasma tube 1.1 cm in diameter and 100 cm long. An electromagnet surrounds the plasma tube, providing an axial magnetic field up to 4.2 kG that helps to direct and confine the electron beam. The electron beam is produced by a glow discharge electron gun, and has an energy between 1 and 5 keV. We operate this glow discharge electron gun in helium at pressures up to 3 torr without differential pumping. The beam electrons are produced at the cathode by secondary emission following bombardment of the

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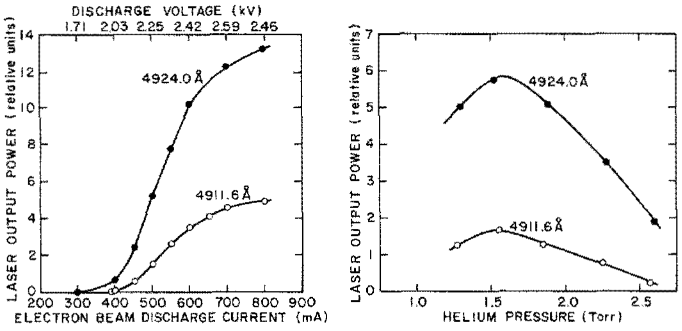
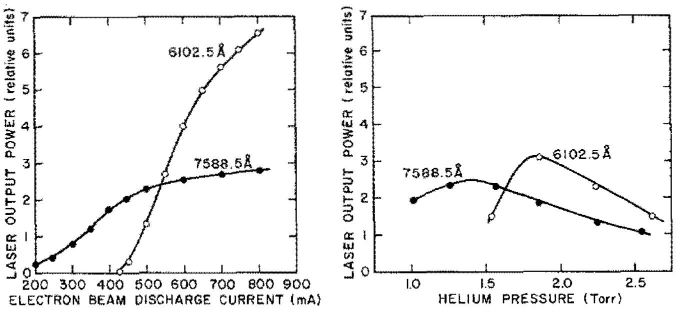


(a) (b)

Fig. 1. (a) Laser output power of the Zn II blue lines as a function of electron beam discharge current and voltage. Average helium pressure in the active medium was 1.5 torr. Magnetic field was 4.2 kG. Zn reservoir temperature was 420°C. (b) Laser output power of the Zn II blue laser lines as a function of the average He pressure in the plasma tube. Electron beam discharge current was 700 mA and the Zn reservoir temperature was 420°C. Magnetic field of 4.2 kG.

aluminum cathode surface by ions and fast neutrals. The emitted electrons are then accelerated through the cathode dark space where practically all the voltage drop of the discharge occurs. The resulting electron beam is well collimated. Using a calorimeter we have measured an electron beam generation efficiency of 60 percent when the glow discharge is operated in helium at a pressure of 1 torr. The glow discharge electron gun provides an optical path throughout the axis [3]. This permits one to easily match the electron beam created plasma volume with the corresponding volume of an optical resonator. A metal vapor trap separates the plasma tube from the electron beam generation chamber. Metal vapor is produced by heating a source reservoir attached to the opposite end of the plasma tube. Helium is flown throughout the plasma tube at 200-400 s · cm^3/min.

The optimum reservoir temperature for CW laser action in zinc was found to be 420°C. Fig. 1(a) shows the output power of the Zn II blue lines as a function of the electron beam discharge current and voltage at a plasma tube average helium pressure of 1.5 torr. At the largest electron beam currents the laser output power of these Zn II lines is observed to increase in a sublinear manner. This behavior is judged to be due to the sublinear increase of the discharge power with current, since the discharge voltage drop at 800 mA was measured to be smaller than at 700 mA, as shown in Fig. 1(a). Fig. 1(b) shows the pressure dependence of the laser output power of the blue Zn II laser lines. The most intense laser lines in Zn II were the blue lines. Using an unoptimized output coupler with a reflectivity of 94.5 percent at 4900 Å we measured a maximum CW laser output power of 60 mW for the combination of the 4911.6 and 4924.0 Å lines. This is comparable to the highest true CW laser output power obtained from hollow cathode devices [5]. Optimizing the optical resonator and the design of the metal vapor trap that presently stops part of the electron beam from reaching the plasma tube an output power of a few hundred mW should be expected in the blue lines of Zn II.



(a) (b)

Fig. 2. (a) Laser output power of the 6102.5 and 7588.5 Å lines as a function of electron beam discharge current at the optimum He average pressures of 1.8 torr and 1.5 torr, respectively. Magnetic field was 4.2 and 3.9 kG, respectively. Zn reservoir temperature was 420°C. (b) Laser output power of the 6102.5 and 7588.5 Å lines of Zn II as a function of He average pressure in the plasma tube at the optimum magnetic fields of 4.2 and 3.9 kG, respectively. Zn reservoir temperature was 420°C. Electron beam discharge current was 700 mA.

Fig. 2(a) and (b) shows the laser output power dependence of the 6102.5 and 7588.5 Å lines of Zn II with the electron beam current and helium pressure, respectively, at the optimum magnetic field for each line. The 7588.5 Å laser line presented the lowest current threshold observed (80 mA), corresponding to an electron beam discharge voltage of 1.4 kV. Output power was not optimized or measured.

Fig. 3 shows the CW laser output power dependence of the 6511.7 Å line of As II as a function of electron beam discharge current. The optimum arsenic source reservoir temperature was 385°C and the optimum helium pressure in the plasma tube was 1.3 torr. To obtain CW laser action on arsenic we used an optical resonator composed by two 2 m radius of curvature total reflectors. The laser output power was considerably smaller than that in the Zn II study and no attempt was made to optimize it.

The dominant excitation mechanism in both lasers is a thermal charge transfer reaction [7] between helium ground state ions and the metal vapor atoms. This results in formation of excited metal vapor ion levels from which the laser action originates. Note that $5p\ ^2P^0_{3/2}$ upper level of the 7588.5 Å line of Zn II is mainly populated by radiative cascade from the higher Zn II energy levels populated by the charge transfer process [7]. Supporting these above arguments we found that no laser action was obtained when we replaced He by Ne in the He-Zn mixture.

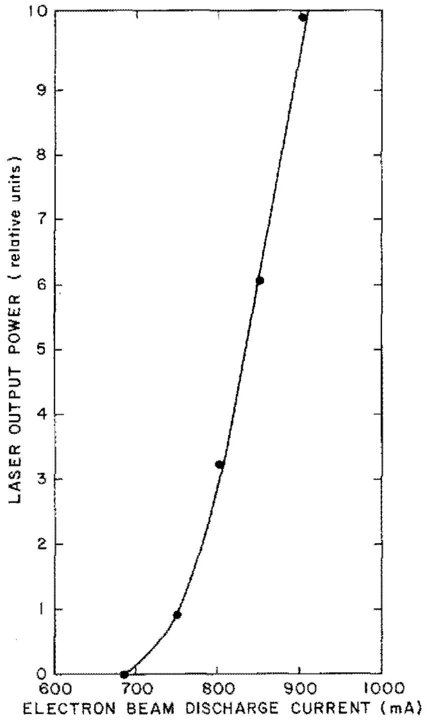


Fig. 3. Variation of the laser output power of the 6511.7 A line of As II as a function of electron beam discharge current. The As reservoir temperature was 387°C and the magnetic field was 4 kG. The helium average pressure in the plasma tube was 1.3 torr. The electron beam energy at 900 mA was 2.7 keV.

CONCLUSION

In summary, we have obtained CW laser action on Zn II and As II using for the first time electron beam excitation. We have demonstrated, as recently suggested [6], that dc electron beam pumping can be used to excite a large variety of ion lasers.

ACKNOWLEDGMENT

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REFERENCES

[1] J. J. Rocca, J. D. Meyer, and G. J. Collins, "Electron beam pumped CW Hg ion laser," *Appl. Phys. Lett.*, vol. 40, pp. 300-302, Feb. 1982.
[2] J. D. Meyer, J. J. Rocca, Z. Yu, and G. J. Collins, "CW iodine laser excited by an electron beam," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 326-327, Mar. 1982.
[3] J. J. Rocca, J. D. Meyer, and G. J. Collins, "Electron beam pumped CW Se II laser," *Opt. Commun.*, to be published.
[4] J. J. Rocca, J. D. Meyer, and G. J. Collins, "Hollow cathode electron gun for the excitation of CW lasers," *Phys. Lett.*, vol. 87A, pp. 237-239, Jan. 1982.
[5] J. A. Piper and P. Gill, "Output characteristics of the He-Zn laser," *J. Phys. D. (Appl. Phys.)*, vol. 8, pp. 127-134, Feb. 1975.
[6] J. J. Rocca, J. D. Meyer, Z. Yu, and G. J. Collins, "Electron beam excitation of CW ion lasers," presented at the 34th Gaseous Electronic Conf., Boston, MA, Oct. 1981.
[7] G. J. Collins, "Excitation mechanism in He-Cd and He-Zn ion lasers," *J. Appl. Phys.*, vol. 44, pp. 4633-4652, Oct. 1973.

Collisional Narrowing in the Optically Pumped CH_3OH and CH_3F Lasers

NABIL M. LAWANDY AND GERHARD A. KOEPF

***Abstract*—The gain linewidth of the optically pumped CH_3F laser is observed to narrow and rebroaden with the addition of He. In addition, we observe the same effect in the CH_3OH laser with the addition of the polyatomic buffer gases SF_6 and CS_2. These results offer conclusive evidence of the Dicke narrowing phenomena in these inverted pure rotational transitions. The effect is observed using a high harmonic mixing technique in a Schottky barrier diode.**

INTRODUCTION

IN 1953, Dicke discussed the effect of collisions which did not disturb the internal emission process of a radiator on the Doppler width of the transition observed [1]. He showed that in the limit that the radiator suffered many velocity-changing collisions during the time it took to travel a distance $\lambda/2\pi$ (λ is the wavelength of the emission), the Doppler width would be greatly reduced. The connection between the Doppler width and the mean velocity is made through the uncertainty principle. The Doppler shift of a photon can only give information related to displacements greater than $\lambda/2\pi$. Therefore, when collisions occur with a mean free path less than $\lambda/2\pi$, the resulting Doppler information does not represent the thermal velocity, but approaches the mean of zero for zero-mean free path.

The collisional narrowing effect has been experimentally verified since 1956 when Wittke and Dicke performed experiments on the 1420.4 MHz hyperfine splitting of atomic hydrogen [2]. In their experiment, they were able to observe the linewidth collapse by a factor of ten under optimum conditions. Subsequent to this work, other microwave measurements were carried out [3]-[7]. The experiments which followed these were at higher infrared and invisible wavelengths. The optical techniques were of a light-scattering nature, while the infrared measurements were performed using absorption spectroscopy [8], [9].

The experiments discussed so far all utilized inert gases as collision partners. In fact, attempts to observe the effect using

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