High power atomic xenon laser

W.J. Witteman, P.J.M. Peters, H. Botma, S.N. Tskhai, Y.B. Udalov, Qi-Chu Mei and V.N. Ochkin

University of Twente, Department of Applied Physics
P.O. Box 217, 7500 AE Enschede, The Netherlands

ABSTRACT

The high pressure atomic xenon laser is becoming the most promising light source in the wavelength region of a few microns. The merits are high efficiency (so far up to 8 percent), high output energies (15 J/litre at 9 bar), high continuous output power (more than 200 W/litre), no gas dissociation and thermal heating of the lower laser level. Compared with the well-known low pressure xenon laser the power performance is now roughly a factor thousand higher. The operation of the system, based on three-body-collisions, uses the metastable state of the xenon atom as the ground state so that in the recirculation of energy a high quantum efficiency is obtained. Furthermore the homogeneous line broadening caused by the high collision frequency has also a strong beneficial effect on the efficiency. However, the required intense homogeneous excitation of the gas medium at high density is from a technical point of view a great challenge. From our experimental and theoretical work we found that at optimum performance the input power must be 1 to 2.5 [KW cm⁻³ atm⁻²]. We describe our results obtained with e-beam sustained and x-ray preionized systems delivering pulsed energies in the range of joules per litre. Furthermore we describe our recent results on continuous RF excited wave guide systems of about 37 cm length with output powers in the range of watts.

Keywords: high atomic lasers, cw and pulsed 2-3 μ m lasers.

1. INTRODUCTION

Laser actions in high-pressure argon diluted with about one percent xenon is very promising for obtaining coherent light in the wavelength region of a few microns. Its major advantages are high efficiency (so far up to 8 percent), high output energies (15 J/litre at 9 bar pressure), high continuous output power (more than 200 W/litre), no gas dissociation and thermal heating of the lower laser level. The major breakthrough in this type of laser was possible after the technology for e-beam and e-beam sustained systems and later the technology for pulsed high pressure discharges with UV and X-ray preionization became available. Especially the e-beam sustained technology which was successfully developed during the eighties for high energy excimer systems is crucial for obtaining high performance in pulsed operation. The important point by applying these very different discharge technologies is the possibility to expand the range of working pressures substantially which turns out to be essential for obtaining higher power and better efficiency. From these observations and the accompanying theoretical modelling the idea was supported to consider a multi-atmosphere xenon laser as a four level system that uses the metastable state of the lasing atom as the ground state in the excitation scheme⁽¹⁾. The primary channels for the filling of the upper laser level in the argon-xenon mixture is the dissociative recombination of ArXe⁺ or Xe₂⁺ molecular ions with electrons. After the ions recombine they decay to form the upper laser level, hence the name "Recombination laser." The lower level is emptied in collisions with atoms of the buffer gas argon and with electrons by decaying to the metastable level. The atoms in the metastable state are then ionised again in the discharge. The high lasing efficiency is a consequence of the fact that the quantum efficiency of the xenon laser increases because of a recirculation of energy without a relaxation of metastable atoms to the ground state. Ionisation from this metastable state requires only 3.8 eV. See fig. 1.

Fig. 1. Four level scheme of the atomic Ar-Xe laser.

The lasing of atomic xenon occurs on the well-known infrared transitions (1.73-3.51 μm) between the 5d and 6p manifolds as shown in fig. 2. The 5d manifold is efficiently populated through the recombination process with a resulting quantum efficiency of 19% for the 1.73 μm line. Although high power operation is obtained the system saturates with increasing electron density i.e. current density. The mixing of the 5d and 6p manifolds by the electrons is always in competition with the stimulated emission process of the laser. With increasing pump power, as we shall see later on, the mixing process wins at the expense of stimulated emission. As a result both lasing efficiency and lasing power decrease above a certain input power level.

The above mentioned recombination is a three-body-collision process. It is the principal mechanism in the inversion process. This can only occur at high gas density, say above 100 Torr. The increased pressure leads also to homogeneous line broadening which has a beneficial effect on the efficiency. However, a homogeneous inversion density under such conditions requires a homogeneous discharge in a high density gas. This is from a technical point of view a great challenge. A self sustained discharge at these densities is in principle unstable. Moreover, at high gas density the pressure broadening mechanism of the laser transitions reduces the gain. At constant inversion density the gain is inversely proportional to the gas density, whereas the saturation intensity increases proportionally to this density. In order to maintain sufficient gain to reach saturation in a laser system it is necessary to increase also the inversion density proportional to the gas density. This means, however, that in a laser volume of, say, 100 cm^3 at one atmosphere gas pressure the input power is of the order of 250 KW. At first glance this is not realistic for continuous operation. For that reason most attention is paid to pulsed systems where during the pulse the input energy is sufficient high and the average power is set by the pulse repetition frequency. The above mentioned technology for pulsed discharges at high pressure has been applied in a modified version to investigate this near infrared atomic laser. Stable short pulse discharges are either UV⁽²⁾ or X-ray^(3,4) preionized, electron beam pumped⁽¹⁾ or electron beam sustained^(1,5).

2. E-BEAM SUSTAINED OPERATION

The dynamic behaviour of the laser can be described by a set of coupled rate equations. The analysis for calculating the total output power can be simplified by considering each of the 5d and 6p manifolds as shown in fig. 2 as an average energy level so that the laser system is approximated at a four-level system. Assuming at high density that the life time of the lower level is inversely proportional to the gas density, we have shown ⁽⁶⁾ that both the optimised input power and maximum output power depend on the square of the gas density. Furthermore, the fractional ionisation i.e. the ratio between the electron density and gas density at maximum output power is independent on the gas density.

Fig. 2. Energy levels of the 5d-6p manifolds of Xe showing the laser transitions.

The experimental parametric studies of the argon-xenon recombination laser have been carried out with the instrumentation described in references 7 and 8. It is an e-beam sustained system. The e-beam electrons are accelerated in a vacuum diode by a high voltage pulse, up to 270 KeV, obtained with a Marx generator and enter the laser head through a $25 \mu\text{m}$ thin titanium foil. The sustainer circuit for the main discharge consists of a capacitor of $5.4 \mu\text{F}$ in series with a resistor of about 0.05Ω to control the current. The energy of this capacitor, charged in the range between 3 and 12 KV, is switched into the discharge by the e-beam. Although the e-beam pulse and sustainer discharge pulse have different durations it is observed that during the simultaneous presence of both pulses strong quasi-stationary laser action is obtained with powers that depend on the e-beam current. After the termination of the e-beam pulse having a duration of $1.2 \mu\text{sec}$ the laser action continues during the few microseconds that the sustainer pulse is still present, but at a considerably lower level. The power density measurements during the quasi-stationary periode have been obtained as a function of gas density up to 9 bar. A typical example of the observed output power density versus input power density is given in fig. 3. The gas mixture contains 0.4 % xenon in 8 bar argon. The e-beam current is 0.8 A/cm^2 with an energy of 180 KeV measured directly behind the transmission foil⁽⁷⁾. The sustainer capacitor is either $1.8 \mu\text{F}$ ($\blacktriangle$) or $5.4 \mu\text{F}$ ($\bullet$). As expected the behaviour of the laser depends on the input power density and not on the capacitor or pulse duration. Under the present conditions an optimum input power of about 150 KW/cm^3 is found, independent on capacitor value and pulse duration. Also the theoretical curve⁽⁶⁾ is plotted in fig. 3.

Fig. 3. Output power density of a 8 bar e-beam sustained Ar-Xe laser versus input power density. The e-beam current density is 0.8 A/cm^2 and the energy 180 KeV. The sustainer circuit contains a serial resistor R_s of 0.1Ω and a capacitor C_s of $1.8 \mu\text{F}$ (▲) and $5.4 \mu\text{F}$ (●).

Further we plotted in figs. 4 and 5 the observed values for P_{opt} , respectively W_{max} versus the square of the gas density for various values of the e-beam current. The figures show the more or less linear dependence on the square of the gas density as predicted theoretically. It is seen that higher efficiencies are indeed obtained with higher e-beam current densities. If the e-beam current or sustainer current is too high or the gas density too low then the electron quenching will terminate for a while the laser process after which it starts at low power⁽⁸⁾. We conclude from fig. 4 that the optimised quasi steady state input power of the atomic xenon recombination laser is, depending on E_0 , about 1 to 2.5 [KW cm⁻³ atm⁻²].

Fig. 4. The observed optimised input power densities versus the square of gas densities for different e-beam current densities. f is the fractional ionisation.

Fig. 5. The observed optimised output power densities versus the square of the gas densities for different e-beam current densities.

3. CONTINUOUS OPERATION WITH OUTPUT POWER IN THE RANGE OF WATTS

In spite of the high gas density requirement the search for making cw systems with significant output power has been continued. Various discharge configurations were investigated. Unfortunately, most attempts were in vain, especially those based on a direct current discharge (dc). One approach to investigate discharge stability with increasing pressure is to narrow the discharge channel according to the similarity rules which state that pressure times discharge diameter is constant. From our research on e-beam sustained operation we deduce, as shown in fig. 4, that the required input power density is about 1 to 2.5 [KW cm⁻³ atm⁻²]. This means that for a narrow channel of about 0.1 cm², an active length of 50 cm and a gas pressure of 100 Torr about 100 to 250 Watt input power is required in order to make full profit of the above mentioned laser mechanism. This requirement is not easy to fulfil, especially because of the high gas density. Even in very narrow capillaries of 1 mm diameter the maximum attainable gas density is still too low for a substantial increase in output power in the case of a dc discharge. Since discharge stability and homogeneity are in general better ensured with a radio frequency (RF) discharge than with a normal dc discharge we explored successfully RF excitation for this lasing gas system as a function of gas pressure⁽⁹⁾. This technique has several benefits. It operates as a transverse discharge between a narrow gap of two parallel electrodes so that a relatively low discharge voltage is sufficient and good spatial homogeneity is obtained. The free choice of the excitation frequency gives an extra parameter to control the gas discharge. A particular advantage to the recombination laser pumping is that the rise and, more important, the fall times of the RF-excitation are independent of the discharge electrical parameters. We obtained uniform RF excited gas discharge plasmas in various laser resonator geometry's including slab systems. So far we obtained⁽¹⁰⁾ for the atomic xenon laser with RF excitation at 125 MHz a cw output power of 1.5 W in a slab configuration with a cross section of 1.5 x 10 mm² and an active length of 37 cm. The gas is a mixture of Ar:He:Xe = 50:49:1 at a total pressure of 90 Torr. The input power is about 300 W. The output power and efficiency as a function of input power are shown in fig. 6.

Fig. 6. The output power (O) and efficiency (□) as a function of input power for a gas mixture Ar-He-Xe (50:49:1) at a pressure of 90 Torr.

4. PREPULSE-MAIN PULSE DISCHARGE WITH X-RAY PREIONIZATION

In a e-beam sustained laser a high population of metastables can be maintained during the period that ionisation is supplied by the e-beam. Operation of this laser in a self-sustained discharge is attractive in view of high repetition operation. Moreover since the system contains only rare gases without aggressive chemical compounds it is expected that high average power operation should be simpler than for excimerlasers.

A self sustained discharge can be obtained by a homogeneous electron avalanche of an initial low density plasma. The low electron density of the initial plasma may be obtained by photo-ionisation of the discharge volume by UV light or X-rays. Directly after this low electron density is created the discharge starts with a fast rise time in the order of 10 nsec. Then with the formation of the discharge the plasma resistivity decreases rapidly and the voltage across the electrodes reaches the so called steady state conditions for which the voltage is more or less constant independent on the current. However since the voltage for rapid breakdown is not consistent with efficient impedance matching of the electric circuit to the laser head we use similar to excimer lasers a avalanche breakdown (prepulse) and a quasi steady state discharge (sustainer), both provided by separate circuits. The scheme is shown in fig. 7.

Fig. 7. The prepulse-main pulse circuits for self sustained discharge. $C_{PFN}=108$ nF, $C_p=5.6$ nF, $C_{spi}=6.95$ nF, $C_c=2.8$ nF

The main pulse is delivered by the low inductance pulse forming network (PFN) connected with a magnetic switch (saturable inductor) to the laser electrodes. This saturable inductor has the form of a race track in order to have low inductance after saturation. The prepulse is fired after charging the peaking capacity C_p . The rise time of prepulse is determined by the charging time of C_p . For that reason we applied pulse compression by transferring the prepulse energy from the charging capacitor C_c to C_p . The laser chamber is a stainless steel vessel. The active region of the discharge is 60 cm, the distance between the electrodes is 2.5 cm and the width is 1.6 cm. Adjustable mirror mounts are situated at the far ends of the pressure cell. The cavity length of 130 cm consists of an aluminium concave ($R=5$ m) end reflector and a plain parallel ZnSe outcoupling plate having about 50% outcoupling. The gas mixture of Ar-Xe contains 1% Xe. The pressure is 1.4 bar. The capacitors C_c and C_p with respectively 2.8 and 5.6 nF are charged at 40 kV. The PFN has 108 nF. The output as a function of the charging voltage V_m of the main line is shown in fig. 8.

Fig. 8. Output and efficiency as a function of the charging voltage of the main line. The charging voltage of C_p is 40 kV.

5. ACKNOWLEDGEMENT

These investigations in the program of the Foundation for Fundamental Research on Matter (FOM) have been supported by the Netherlands Technology Foundation (STW).

6. REFERENCES

1. N.G. Basov, V.V. Baranov, A.Y. Chugunov, V.A. Danilychev, A.Y. Dudin, I.V. Kholin, N.N. Ustinovskii and D.A. Zayarnyi, *IEEE J. Quantum Electron.*, **21**, 1756 (1985).
2. D.E. Rothe and K.V. Tan, *Appl.Phys.lett.*, **30**, 152 (1977).
3. J.E. Tucker, B.L. Wexler, B.J. Feldman and T. Mc Clelland, *IEEE Phot.Technol.Lett.*, **1**, 193 (1989).
4. J.E. Tucker and B.L. Wexler, *IEEE J. Quantum Electron.*, **26**, 1647 (1990).
5. L.A. Newman and T.A. De Temple, *Appl.Phys.Lett.*, **27**, 678 (1975).
6. W.J. Witteman, P.J.M. Peters, H. Botma and Y.B. Udalov, *Infrared Physics* (to be published).
7. H. Botma, P.J.M. Peters and W.J. Witteman, *Appl.Phys.B.*, **52**, 277 (1991).
8. H. Botma, P.J.M. Peters and W.J. Witteman, *IEEE J. Quantum Electron.*, **29**, 2519 (1993).
9. Y.B. Udalov, P.J.M. Peters, M.B. Heeman-Ilieva, F.H.J. Ernst, V.N. Ochkin and W.J. Witteman, *Appl.Phys.Lett.*, **63**, 721 (1993).
10. S.N. Tskhai, Y.B. Udalov, P.J.M. Peters, W.J. Witteman and V.N. Ochkin, Submitted to *Appl. Phys. Letters*.