High specific laser output energy at 157 nm from an electron beam pumped He/Ne/F_2 gas mixture

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(Received 27 May 1993; accepted for publication 13 September 1993)

The output energy and the temporal behavior of a molecular F_2^* laser pumped by a coaxial electron beam have been measured in gas mixtures of He/F_2 and He/Ne/F_2. The highest output energy of 172 mJ has been obtained in a mixture of He/Ne/F_2 (19.9%/80%/0.1%) at a pressure of 12 bar, corresponding to a specific output energy of 10.8 J/ℓ and an intrinsic efficiency of 2.6%.

Coherent light sources in the vacuum ultraviolet (VUV) are of growing interest for their applications in lithography, spectroscopy, ablation processes, biology, etc. In addition to the well-known rare-gas dimer lasers like Xe_2^*, Ar_2^*, and Kr_2^*, the molecular F_2^* laser at 157 nm is a powerful laser source in the VUV.

An electron beam pumped F_2^* laser was demonstrated first by Rice *et al.* in 1977.[1] A specific output energy of 0.0024 J/ℓ was reported from a He/F_2 gas mixture at a total gas pressure of 2 bar. They also showed an efficient operation at very high pumping rates at high pressures.[2] At a total gas pressure of 10 bar a specific output energy of 1.76 J/ℓ was found. In 1979, for the first time a discharge pumped F_2^* laser was described.[3] In 1986 a theoretical paper on electron beam pumped F_2^* lasers was published by Kim *et al.*[4] Recently Bastiaens *et al.*[5] showed that the small signal gain coefficients in neon-doped He/F_2 laser gas mixtures, pumped by a coaxial electron beam, were higher than in the normally used He/F_2 mixtures, probably caused by the higher pumping rate at the same gas pressures. In this letter we describe the results of measurements in which the output energy, temporal behavior, and intrinsic efficiency of such a coaxial electron beam pumped F_2^* laser are evaluated for neon-doped He/F_2 gas mixtures.

The F_2^* laser requires a very high pumping power. In our experiments we used a coaxial electron beam as pumping source. Details of this system have been reported elsewhere.[6] The gas mixture is contained in a titanium tube of 10-mm diam and a wall thickness of 25 μm. The diameter of the optical beam is limited to 9 mm. The tube acts as an anode in a coaxial diode which is powered by a ten-stage Marx generator delivering a negative voltage pulse with a peak value of 300 kV and a width of 50 ns (FWHM). The excitation current, as measured with a Faraday cup inside the tube, has a triangular shape with a pulse width of 25 ns (FWHM). The excitation length is 25 cm. The power deposition in the laser gas mixture is measured by the pressure jump technique. At the maximum load voltage of the Marx generator the power deposition in He is 0.47 MW/cm^3/bar while in Ne a value of 1.3 MW/cm^3/bar can be achieved.

The first laser attempts were done in a resonator with an aluminized rear mirror as a total reflector and a MgF_2 window output coupler. Unfortunately the high VUV pulse energy damaged the aluminum coating of the rear mirror. To solve this problem, a double MgF_2 cavity configuration, as has been investigated by Hooker *et al.*,[7] and which takes energy out of both ends, can be used.

In Fig. 1 the experimental setup is shown. The resonator consists of two MgF_2 windows at a distance of 44 cm from each other. The laser beam emerging from the right window is detected by a pyroelectric energy meter (Gentec ED 500). A MgF_2 lens is used to expand the beam to avoid damaging the detector surface by the high VUV pulse intensities. The optical beam on the right-hand side of the resonator is sent through a tube which is kept at a pressure of 10^{-5} mbar. On the left-hand side the laser beam is sent to a tilted MgF_2 window. The transmitted beam can be visualized on UV sensitive paper. The reflected beam hits a scintillator plate which converts the VUV radiation into radiation that can be detected by a silicon photodiode (EG&G, FND 100 Q), so the temporal behavior of the output pulse can be recorded. A filter is placed between the scintillator material and the photodiode to exclude the possibility of detection of the red emission originating from the atomic fluorine laser.[8] To avoid attenuation of the 157 nm radiation due to absorption of molecular oxygen, present in the atmosphere, the optical path on the left-hand side of the laserhead is continually flushed by very pure nitrogen (purity > 99.999%).

In Fig. 2 a typical F_2^* laser pulse is shown, together with the excitation current as was measured inside the tube. The optical pulse is delayed from the excitation pulse by approximately 25 ns at a total gas pressure of 4 bar. The delay decreases to 12 ns at 12 bar. The rise time of the laser pulse is always 14±1 ns. The pulse width is 35 ns in this case but depends on gas pressure and gas composition.

In Fig. 3 the VUV pulse energy as measured with the

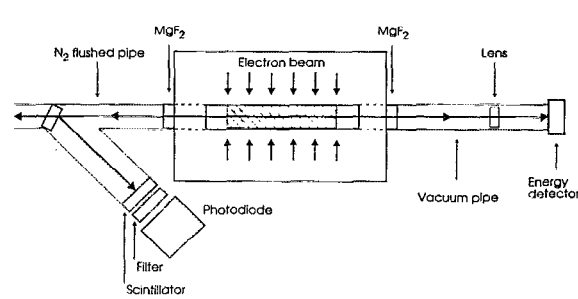

FIG. 1. Schematic representation of the experimental setup.

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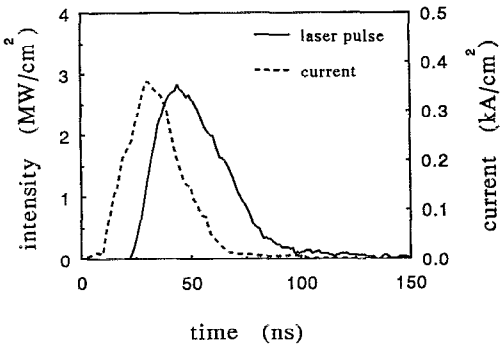

FIG. 2. Temporal behavior of a typical F_2^* laser pulse (solid line) and the excitation current (dotted line).

Gentec is shown as a function of the neon fraction for $He/Ne/F_2$ mixtures with 0.1% F_2 at various total gas pressures. The output energy increases considerably when neon is added to a He/F_2 mixture, but the rate of increase declines with increasing neon fraction. It also can be seen from this figure that the output energy increases with pressure. The maximum energy measured on the right side of the resonator was 86 mJ (3.2 MW/cm^2) for a laser gas mixture with a neon fraction of 80% at a total gas pressure of 12 bar. Assuming 86 mJ also emerging from the left-hand side, the total laser output energy was 172 mJ, which corresponds to a specific output of 10.8 J/ℓ and an intrinsic efficiency of 2.6%.

The laser output energy dependence on the F_2 concentration also was investigated for a gas mixture with a constant Ne fraction of 60% at different total gas pressures. An optimum occurred for a F_2 fraction of 0.1% at total gas pressures above 6 bar. For F_2 fractions of 0.05% and 0.2% the laser output energy was halved compared to 0.1% F_2. The delay time between the internal excitation current and the optical pulse decreased with increasing F_2 fractions.

Figure 4 shows the measured VUV pulse energy, measured on one side, as a function of total gas pressure for $He/Ne/F_2$ mixtures with 0.1% F_2 at various neon fractions. During these measurements the power deposition in the different gas mixtures was kept constant at 4 MW/cm^3 by varying the load voltage of the Marx generator. Looking

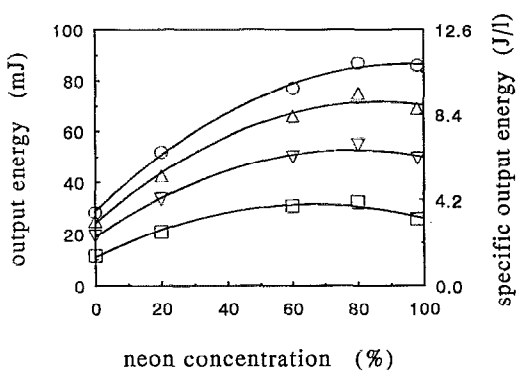

FIG. 3. Laser pulse energy (as measured on one side) in $He/Ne/F_2$ gas mixtures with 0.1% F_2 as a function of the neon concentration for various total gas pressures (□: 6 bar; ▽: 8 bar; △: 10 bar; ○: 12 bar).

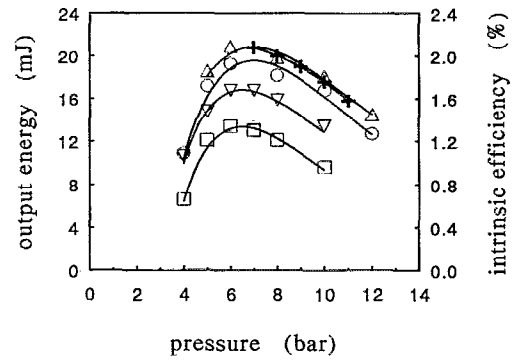

FIG. 4. Laser pulse energy and intrinsic efficiency in $He/Ne/F_2$ gas mixtures with 0.1% F_2 as a function of the total gas pressure for various neon concentrations. The power deposition was kept constant at 4 MW/cm^3 (+: 0% neon; △: 20% neon; ○: 60% neon; ▽: 80% neon; □: 98% neon).

at the optima of the curves, the efficiency of mixtures with neon fractions of 0% and 20% is almost equal to 2.0%. At higher neon fractions the efficiency starts to decrease, ending at 1.3% for a Ne/F_2 mixture. For a constant power deposition there exists an optimum pressure where the highest output energy (and the highest efficiency) is obtained. This behavior is easily understood, because for a given power deposition a certain threshold pressure is needed to obtain laser action. By increasing the pressure above threshold, energy couples out as laser emission. Two processes can be responsible for the decrease of the output energy above the optimum pressure. The first one is quenching of the upper laser level or quenching of precursors for the formation of the upper laser level. An effective quencher of the upper laser level is F_2, given the large quenching rate constants as can be found in literature.[9,10] Absorption of radiation by absorbing species in the gas mixture also may decrease the output energy. Possible absorbers are the upper laser level itself, excited states of F atoms, or when He and/or Ne is used in the gas mixture also excited states of He and/or Ne.[11,12] The optimum pressure is about 7 bar for this power deposition and is not strongly dependent on the neon fraction.

Recently the small signal gain in an electron beam pumped molecular F_2^* laser has been measured by Bastiaens *et al.*[5] Their measurements showed an optimum in the small signal gain of $He/Ne/F_2$ mixtures at a Ne fraction of 60%. The explanation for an optimum to occur was the increasing power deposition at higher Ne concentrations, but because of the decreasing formation efficiency (in $He/Ne/F_2$ mixtures) the enlarged power deposition will be counterbalanced, and eventually will lead to a decrease of the small signal gain for Ne fractions exceeding 60%. From Fig. 4 the decreasing efficiency at higher Ne fractions is confirmed, and this is also the reason the output energy curves from Fig. 3 saturate, although the power deposition increases linearly with increasing Ne fraction. A possible explanation for the decreased efficiency in Ne/F_2 mixtures could be the fluorescence losses of NeF* (107 nm).[9] Direct quenching of the upper laser level by Ne is

not likely to be important, as can be deduced from the reported low quenching rate constant for this process.[9]

In Fig. 2 it was shown that a delay exists between excitation pulse and optical pulse. Because of the high gain in electron beam pumped F_2^* lasers, this delay is not caused by a long ring up time, but probably by rather slow reaction kinetics. The main reaction channel that populates the upper F_2^* laser level is given by

$$F^* + F_2 \rightarrow F_2^*(D) + F. \quad (1)$$

The rate constant for this reaction is about 5×10^{-10} cm^3/s, so the characteristic time constant for the gas mixtures used is about 10 ns. The effective lifetime of the upper laser level is about 3 ns,[10,13] which means that the temporal behavior of the upper level is determined by the time dependency of the excited fluorine atoms F*. Formation of F* is predominantly determined by electron attachment to F_2 producing F^- ions, followed by ion–ion recombination producing the excited fluorine atoms. These steps cause the delay between excitation and optical pulse. The delay time decreases with increasing F_2 fraction, which can be explained by the faster reaction kinetics leading to F*, and by the increasing formation rate of the upper laser level itself given by reaction (1). It is well known that for He/F_2 mixtures there is a broad region where the output is almost independent of the F_2 concentration.[2,7] Ne/F_2 mixtures show a stronger dependency on the F_2 concentration. If the concentration F_2 is too low, the laser output energy is limited by slow reaction kinetics. This also causes a shortening of the optical pulse. Higher F_2 concentrations not only quench the upper level of F_2^* but also show an increased absorption due to photodetachment of F^- ions. The increased power deposition in $He/Ne/F_2$ mixtures results in higher F^- concentrations, which leads to a rapid decrease of the efficiency at higher F_2 concentrations compared to He/F_2 mixtures.

In conclusion, we have shown that the laser output energy in an electron beam pumped F_2^* laser can be increased considerably when $He/Ne/F_2$ gas mixtures are used instead of the usual He/F_2 mixtures. This increase is due to the higher energy deposition in Ne compared to He. Because of the somewhat lower intrinsic efficiencies in Ne-doped mixtures, the laser energy saturates at higher Ne fractions. A maximum laser output energy of 172 mJ has been obtained from a gas mixture of $He/Ne/F_2$ (19.9%/80%/0.1%) at a total gas pressure of 12 bar and a pumping power density of 13.6 MW/cm^3, corresponding to a specific output of 10.8 J/ℓ and an intrinsic efficiency of 2.6%.

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