Spectral investigation of cw rf-pumped atomic Xe laser with a slab geometry

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Abstract. A radiofrequency excited atomic Xe slab laser with an active volume of $2 \times 10 \times 300 \text{ mm}^3$ using a quartz envelope containing the laser-gas mixture shows a stable cw performance with an output power of almost 1 W. The free-running system oscillates, depending on gas composition and density, on several lines between 1.73 and $3.51 \mu\text{m}$. Line competition phenomena are observed. Single-line oscillation yields more than 500 mW.

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In our previous paper we presented experiments with a continuous wave (cw) radiofrequency (rf) excited atomic Xe laser in a slab geometry having aluminium electrodes. A laser output power of 1.5 W and an efficiency of up to 0.8% were reported [1]. The main problem with this system was that its operation lasted for a relatively short time at the high output level. The output power decreased rather strongly after about 1 min. After 5–10 min of operation, during which the output level decreased considerably, a more stable regime was obtained. Although the measured input power also decreased with time, the decrease in output power was faster, probably due to changes in discharge properties [2] and to electrode effects [3]. Apparently, the discharge was perturbed by impurities. In this article we report on our investigation of a cw Xe laser in a slab geometry with the rf electrodes mounted outside the laser-gas volume. In this configuration the laser gas is contained in a closed rectangular thin quartz or pyrex glass tube and the electrodes are located close to the outer wall of the tube.

1 Experimental setup

We used a rectangular quartz tube of 40 cm length, an inner dimension of $2 \times 10 \text{ mm}^2$ and a wall thickness of

1 mm. Along both sidewalls of the tube two flat aluminium electrodes ($10 \times 300 \text{ mm}^2$) were placed. The distance between the electrodes was 4 mm. All experiments presented here were performed with the electrodes cooled down to about 12°C .

For the optical resonator a plane-parallel configuration with a totally reflecting gold-coated mirror and a dielectric coupling mirror with 45% reflectivity in the spectral range from 1.7 to $3.5 \mu\text{m}$ was used. The total length of the resonator was 45 cm. In some experiments we replaced the totally reflecting mirror by an aluminium-coated grating with 300 lines/mm blazed at $5.4 \mu\text{m}$.

The grating was used in the second order. The generated laser spectrum was analysed with a monochromator (SPEX 1681) equipped with a 300 lines/mm grating. More details of the setup are given in previous papers [1, 4]. The input power was varied from 80 to 400 W, the laser-gas pressure from 60 to 400 mbar and the rf excitation frequency was 112.5 MHz. In the Ar–He–Xe laser-gas mixture the Ar concentration was varied from 0 to 99.5% and the Xe concentration from 0.02 to 10%. Some experiments with Ar–Ne–Xe gas mixtures containing Ne up to 40% have been performed also.

2 Experiments and discussion

In Fig. 1, the temporal behaviour of the laser parameters is shown. The gas mixture was Ar–He–Xe (60:39.5:0.5) at a total pressure of 120 mbar. As one can see, the output power of this laser drops less than 10% during 1 h of operation. The first several minutes the output power even increases a bit.

Looking more precisely at the first minutes of the laser operation we see in an Ar-rich gas mixture directly after the discharge ignition a more or less pronounced peak in the laser output power which is not visible under other conditions. As can be seen from the inset in Fig. 1, after a short time this peak drops down again and then the output power starts to increase like in the conventional long-time operation regime. A similar behaviour occurred

Fig. 1. Time dependence of the laser output power (laser-gas mixture Ar:He:Xe = 60:39.5:0.5, total pressure of 120 mbar; *inset*: laser-gas mixture Ar:He:Xe = 75:24.5:0.5, total pressure 160 mbar, $P_{in} = 350$ W)

in the laser with metal electrodes [1]. This initial peak in the output power increases with the Ar concentration and/or the input power in both lasers. The differences between the two systems are the height of the first peak and the level of the stationary output power. In the electrodeless laser the initial peak output value is lower than in the laser with metal electrodes, but the stationary output level for the laser with metal electrodes was several times lower at higher Ar concentrations. Moreover, in the electrodeless laser the stable output level is higher than the peak value.

In [2] the intensity profiles between the electrodes were measured for both the α - and γ -discharge. It appeared that the intensity of the γ -discharge in the centre between the electrodes was considerably higher than for the α -discharge. This was also observed by us during the first minutes when a bright discharge starting in the center is filling up the tube in the longitudinal direction. We checked the temporal behaviour of the emission intensity of several Ar, He and Xe lines from different parts of the discharge tube through the sidewall. In some part of the discharge the intensity increases with time, in other parts it is stable while the power output increases. If the main channel for the excitation of the emitted line is direct electron impact, it means that the electron and/or current density in this part increases in time, which in turn means that the discharge is gradually transformed from the intermediate to the γ -discharge form.

The output characteristics of this laser are lower compared to the results presented in [1]. This is explained by the shorter active medium length and the additional losses of the electric power in the quartz walls. In Fig. 2 the output power dependency on the input power at different pressures of the Ar-He-Xe (60:39.5:0.5) gas mixture is shown. One can see that the optimal input power for the maximum power output shifts to a larger value as the pressure increases. In the first stage, the maximum power output and efficiency increase with the increase of pressure. However, at a pressure higher than about 200 mbar these values start to drop. The maximum efficiency of $\sim 0.4\%$ was obtained at a pressure of 160 mbar and an

Fig. 2. Laser output and efficiency as a function of the input power at different pressures (gas mixture Ar:He:Xe = 60:39.5:0.5)

input power of 150 W. This result differs strongly from the value in [1]. The efficiency is lower and it does not increase with an increase in input power. The lower value for the efficiency can be explained by additional losses in the quartz walls. The difference in behaviour due to the change of the input power is not so easy to explain. It seems to result from the existence of the two different excitation mechanisms in the laser which can be seen in the temporal behaviour of the laser output power as mentioned above. The mixture used in Fig. 2 (Ar-He-Xe = 60:39.5:0.5) seems to be optimal for a long-time laser operation but not for the short initial peak power as measured in [1] and shown in Fig. 1.

In Fig. 3 an optimisation of the output characteristics with respect to the laser-gas mixture is presented. The optimisation of the output power with respect to the Ar/He content in the laser-gas mixture containing 1% Xe is presented for a total pressure of 100 mbar while the input power was kept at 170 W. It is clear that the optimum Ar concentration is about 60%. The dependence of the power output on Xe is plotted in the same figure for a gas mixture of about 60% Ar and 40% He at a pressure of 100 mbar and an input power of 190 W. Except for a very low Xe concentration we see that the output power does not change very much up to a percentage of 1–2% Xe. With a higher amount of Xe the laser output power decreases strongly, which is in accordance with the calculated results.

Up to now the output characteristics were presented for the integrated output power without any information about the spectral content. Of course, with a change of the external pumping or gas parameters the generated spectrum may change, too. We investigated the spectral composition of the laser with a broadband and a selective resonator.

In Fig. 4 the relative intensities of the different spectral lines of the laser are presented as a function of the gas mixture composition with a non-selective resonator. The measured spectrum differs from the one typical for high-pressure pulsed atomic Xe lasers [6]. There are two lines with $\lambda = 2.48$ and $3.11 \mu\text{m}$ which are usually absent in

Fig. 3. Output power dependency as a function of the Ar/He concentration in a laser-gas mixture with 1% Xe at a pressure of 100 mbar. The input power was 170 W. The dependence on the Xe concentration in an Ar–He–Xe gas mixture at a total gas pressure of 100 mbar is also shown. The ratio Ar/He was 3/2 and the input power in this case was 190 W

a pulsed laser. Only the line with $\lambda = 2.48 \mu\text{m}$ was observed before in a pulsed mode with Kr as the buffer gas [7]. The lines already have been obtained in a laser with rf excitation but only in the pulsed mode [8,9]. The generated spectrum in a gas mixture containing Ar–Ne–Xe is the same as in an Ar–Xe mixture. Ne as a buffer gas does not influence the generated spectrum in the same way as He by depopulating the lower laser level in a selective way [10,11]. As reported earlier for pulsed systems [12], it can be seen from Fig. 4 that lines sharing the upper laser level influence each other. When the He concentration decreases, the intensity of the $2.03 \mu\text{m}$ line decreases while the intensity of the $2.65 \mu\text{m}$ line increases at the same time; both lines start from the same upper level $5d[3/2]_1$. A similar effect occurs for the 3.37 and $2.63 \mu\text{m}$ lines, having the same upper level $5d[5/2]_2$, and the 2.48 and $3.11 \mu\text{m}$ lines starting from $5d[5/2]_3$. The last pair of lines, however, have very low intensities and are not plotted. The line competition effects of these lines result from different depopulation rates of lower laser levels by Ar and He [10]. For the lower laser level of the $2.03 \mu\text{m}$ transition, the rates are 7.49×10^{-11} and $0.5 \times 10^{-11} \text{ cm}^3/\text{s}$ for He and Ar respectively, while for the $2.65 \mu\text{m}$ transition, rates of 2.0 and $20.0 \times 10^{-11} \text{ cm}^3$ (for He and Ar, respectively) are given. It is still not completely clear to us why the laser line with $\lambda = 1.73 \mu\text{m}$, which is the most pronounced line in a pulsed Xe laser, is absent or has such an extremely low intensity in our configuration with rf excitation. The relative intensities of the different spectral lines as a function of the Xe fraction are presented in Fig. 5. The experimental conditions are the same as those in Fig. 3. The behaviour of the intensities of the individual lines for different Xe concentrations is the same as predicted by Ohwa and Kushner [5] for a high-pressure e-beam pumped device. The only difference is that in our case the $2.03 \mu\text{m}$ line intensity behaves as the $1.73 \mu\text{m}$ line in their high-pressure model. When the Xe concentration exceeds

Fig. 4 Relative intensities of the spectral lines as a function of the Ar concentration. The total pressure was 120 mbar, either He or Ne was used as second buffer gas, the Xe concentration was 0.5% and the input power was 220 W

2%, the $2.03 \mu\text{m}$ line (or $1.73 \mu\text{m}$ in the Kushner model) is gradually replaced by the 2.65 or $3.37 \mu\text{m}$ line. According to [13], the gain of the $2.65 \mu\text{m}$ transition is higher than that of the $2.03 \mu\text{m}$ line, which may cause a stronger decrease of the latter line when the same $5d[3/2]_1$ upper laser level is strongly quenched by Xe.

We next investigated the generated laser spectrum in a selective resonator using a grating. In this way the competition between different lines was prohibited. In an Ar–He–Xe (70:29.5:0.5) gas mixture at a pressure of 140 mbar, the relative intensities of the lines with $\lambda = 2.03$, 2.65 , 1.73 , 2.48 , 3.37 , 3.51 and $2.63 \mu\text{m}$ were found to be 1.0, 0.89, 0.09, 0.07, 0.035, 0.01 and 0.0004, respectively. For the first time we got the line with $\lambda = 1.73 \mu\text{m}$ but its intensity was 10 times less than the $2.03 \mu\text{m}$ line. The above-mentioned intensity ratio is close to that for the transition probabilities of these lines [14]. In a gas mixture containing Ne instead of He (Ar–Ne–Xe = 70:29.5:0.5) at the same pressure of 140 mbar, the relative intensities for the different lines 2.65 , 2.03 , 2.63 , 3.37 , $3.11 \mu\text{m}$ were completely different, namely 1.0:0.47:0.37:0.2:0.09. It is very interesting that the $1.73 \mu\text{m}$ line is absent in this case again. It is seen then that the $2.65 \mu\text{m}$ line is much stronger than the $1.73 \mu\text{m}$ line which in a pulsed laser with an Ar-rich gas mixture at a low excitation level has about the same or higher intensity [4]. In our case the power input was $\sim 215 \text{ W}$ ($\sim 36 \text{ W/cm}^3$). This pump rate is comparable with fission-fragment excited Xe lasers [15] having $1.73 \mu\text{m}$ as the most intensive line but with an input power that is substantially less than the high input power densities in pulsed lasers with e-beam excitation. The saturation intensities of the 2.65 and $1.73 \mu\text{m}$ transitions are strongly different [13]. Perhaps in our system it may be possible to change the relation between the 2.65 and $1.73 \mu\text{m}$ line intensities at a higher input power when the $2.65 \mu\text{m}$ transition will be saturated. On the other hand, our results with a selective resonator show that in this laser not only the mechanism of the upper laser level excitation is different from that of high-pressure pulsed laser systems (see Fig. 2) but also there is a difference in lower laser level depopulation.

Fig. 5 Relative intensities of the spectral lines as a function of the Xe concentration. The experimental conditions are the same as in Fig. 3

In the selective resonator we investigated also the single-line behaviour for different gas mixtures and power input levels. In Fig. 6 the dependence of the intensities of the stronger 2.03 and 2.65 μm lines on the input power are shown for two Ar–He–Xe (60:39.5:0.5) and (80:19.5:0.5) gas mixtures at a pressure of 140 mbar. For a gas mixture with the Ar/He ratio of 3/2, one can note that at a low input power level the output power of the 2.65 μm line is higher than that of the 2.03 μm line. It results from the lower lasing threshold of the 2.65 μm line [6]. Unfortunately, it is impossible to investigate this behaviour at input powers less than 100 W since the γ -form discharge does not fill the whole quartz tube in this case. When the power input increases, the 2.65 μm line intensity saturates more quickly than the 2.03 μm one. In a gas mixture with the Ar/He ratio of 4/1, the two lines have the same behaviour, but this mixture substantially differs from the other gas mixture. At a low input power level the output power and/or efficiency are higher in Ar-rich gas mixtures. But the optimal output power was observed at a lower input power and had a lower value compared to the other gas mixture. From this curve it is possible to understand the increase of the laser efficiency with aluminium electrodes when the gas mixture is enriched by Ar [1]. But the value of 0.8% obtained in that laser at 120 W of input power with a gas mixture Ar–He–Xe (79:20:1) was the maximum possible one according to Fig. 6. However, it can be different for the “peak” and for the “stable” laser.

In conclusion, we have shown that it is possible to construct a cw atomic Xe laser with a stable output power by using a quartz rectangular envelope containing the laser-gas mixture and rf electrodes mounted outside along this tube. In a broadband resonator, line competition effects have been observed. From experiments with

Fig. 6 Output power of the single laser lines as a function of the input power for different gas mixtures. The total gas pressure was 140 mbar

a single line cavity, it appeared that the use of Ar and/or He as a buffer gas has a strong influence on the intensities of the different laser lines.

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