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Lifetime tests of rf-excited atomic xenon lasers

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Abstract. In this article we have, for the first time, performed a series of lifetime tests for the continuous wave radiofrequency-excited atomic xenon laser in the 1.7–3.9 μm regime. Different constructions and electrode materials are used to investigate the usefulness of this laser during long-term sealed-off operation. The influence of electrode material on wall–plasma interactions and the effect of gas impurities on the long-term operation of the laser are investigated and discussed.

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The continuous wave (cw) low-pressure direct-current (dc) excited atomic Xe laser in the 1.7–3.9 μm region is well known since the sixties as a high-gain (even superradiant) low-power (less than 1 mW) device. A few years ago this laser was rediscovered as a high-power one (watts level) when using a transverse slab radiofrequency (rf) excitation at elevated pressure. This new configuration, making use of a three-body recombinational cw mechanism [1], has been a subject of subsequent studies ever since (for example [2–4]).

For practical applications of this laser an important parameter is the lifetime of sealed-off systems. It was already pointed out in early reports that, for discharges for Xe-ionic and Xe-neutral lasers with low-pressure (≈ 1 mbar) Xe-containing gas mixtures, there is a problem to support the appropriate amount of Xe [5]. It was explained as gas hardening in the discharge vessel. To compensate this effect, special Xe dosators were added to the systems [6]. Similar peculiarities have been mentioned in recent studies of new rf-excited slab lasers [2, 7]. The gas pressure in the rf-excited systems is much higher ($\approx 10^2$ mbar), but the Xe-fraction in mixtures with Ar and He is typically small ($\approx 10^{-2}$). Therefore the temporal behavior of the Xe density can still be critical for lasing. Evidently the gas mixture and laser output power stability depend on many factors including the discharge structure materials. It is the subject of the presented paper to investigate these parameters in experimental tests.

1 Experiment

The properties of three types of rf-excited laser heads have been investigated experimentally. The different designs of the three laser heads will be discussed. In the next paragraph the results, obtained with these three different types, will be discussed and compared.

1.1 Metal electrodes

In experiments with bare metal electrodes and variable discharge gaps we used a remountable construction with O-ring vacuum tightenings. This construction is described and illustrated in [8]. The electrodes had a length of 37 cm, the width was varied from 2.5 mm to 12 mm, and the interelectrode gap was varied in the range from 0.5 mm to 4 mm.

1.2 Dielectric envelope

In experiments with dielectric walls we used a pyrex envelope with a rectangular inner cross section of $2 \times 10\,\text{mm}^2$ and a wall thickness of 1 mm. Two external aluminum electrodes of 30 cm length and 10 mm width were placed against the envelope on opposite sides. As an alternative, the experiments have also been performed with cylinder tubes of quartz, pyrex and Al_2O_3, all having an inner diameter cross section of 2 mm. In all cases the wall thickness was 1 mm. For all cylinder tubes we used two aluminum electrodes of 25 cm length and 4 mm width, placed along the tubes.

In the laser heads of types 1 and 2 we used flat semi-transparent mirrors to form the laser cavities. The residual gas pressure before filling was typically $(1\ldots4) \times 10^{-6}$ mbar,

the gas pressure varied in the range of 60–260 mbar and the rf excitation field frequency was in the range of 60 to 180 MHz.

1.3 Welded system

The third set of experiments has been carried out with the slab waveguide laser design shown in Fig. 1. This laser head, a metal waveguide with discharge dimensions of $2.5 \times 30 \times 230\ \mathrm{mm}^3$, consists of two plane electrodes produced from covar, an alloy of Ni and Co. For the optical resonator the back concave mirror has a curvature of 5.00 m and the front convex mirror has a curvature of 4.44 m. The mirrors were produced from oxygen-free copper with a HfO_2 coating. The laser radiation was extracted through a quartz window in the laser house.

All connections of the laser head tube are vacuum leak-proof and were constructed using high-temperature soldering, laser welding, and micro-plasma welding. The discharge structure was annealed in vacuum at a temperature of 650 °C during 4 h before assembling and adjusting of the optical elements of a resonator. After this treatment the device was tested for leak-proofness using a He leak detector.

A rf power supply of 2×300 W at a frequency of 81.36 MHz is used for laser pumping. The power supply is connected with the laser head by means of two coaxial cables with a characteristic impedance of 50 Ω. Effective transmission of the rf energy to the discharge plasma is provided by matching devices, made with autotransformer circuits, that are connected with the electrode ends of the laser head structure. An inductance corrector is connected at the center of the electrodes to provide a uniform voltage distribution for the discharge along the electrode structure.

In this experiment the gas pressure was 120 mbar. In all experiments the gas mixture had the composition He : Ar : Xe = 40 : 59.5 : 0.5.

1.4 Gas composition control

In the third set of experiments a mass-spectrometric control of the laser gas was performed. The laser is connected to a high-vacuum system with a set of valves. This setup is shown schematically in Fig. 2. A mass-spectrometric analyzer, type MI-1201, was used to analyze the working gas mixture of the laser.

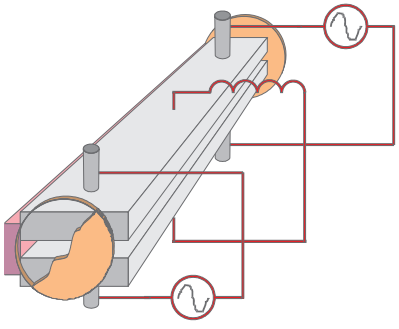

Fig. 1. Schematic diagram of the laser construction

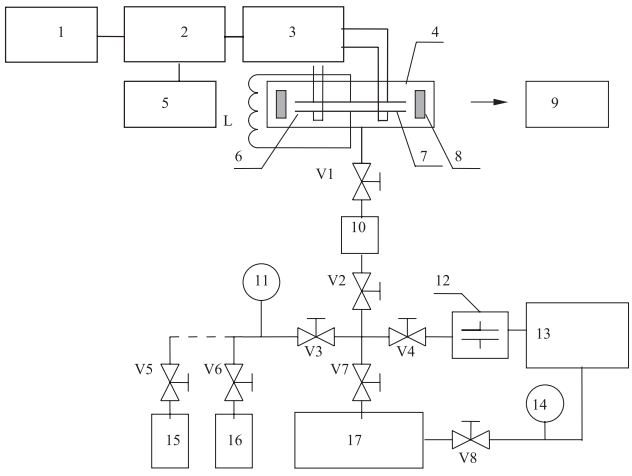

Fig. 2. Experimental system scheme. 1 – low-frequency pulse generator; 2 – RF power supply; 3 – matching network; 4 – discharge chamber; 5 – transformer 220/30 V; 6, 8 – high-reflective mirrors; 7 – discharge structure; 9 – power meter; 10 – test chamber; 11, 14 – vacuum meters; 12 – diaphragm stream; 13 – mass-spectrometric analyser; 15, 16 – gas balloon; 17 – vacuum pumping system; L – corrector inductance; V1–V8 – vacuum valves

Before the experiment started, the laser was subjected to a thermal-vacuum treatment. This treatment consisted of the exhaustion of the vacuum volume during 12 h at a temperature of 120 °C. Mass-spectrometric analysis of the gases released from the walls showed that the residual gas was mainly water vapor. The temperature is limited by the heat resistance of the dielectric coatings of the optical elements of the laser. At the end of the treatment the pressure of the residual gases does not exceed 10^{-8} mbar. After that treatment the laser head was filled with the gas mixture composition controlled by a vacuum meter with an accuracy of ±0.5%. Before starting the measurements, the pressure of the residual gases in the analyzer chamber of the ion source does not exceed 8×10^{-9} mbar.

Prior to the measurements, the analyzer has to be calibrated with respect to all the gas species that can be expected during operation of the laser. The occurrence of these gas components has been investigated and the values of the calibration constants were obtained.

2 Results and discussion

2.1 Metal electrodes

The experiments of type 1 with Al and Cu electrodes demonstrated a rather fast degradation of the laser performance. For this reason these materials have no good perspectives for practical laser applications. In Fig. 3 a typical temporal behavior of the output power of this laser is presented. It can be seen that the output power drops a factor of two within the first 2–3 min and after about 15 min its value is about 30 times smaller than its initial value. From Fig. 3 it can also be seen that the laser power degradation is correlated with the changes of discharge plasma properties. The matching network parameters have been tuned for optimal power transfer

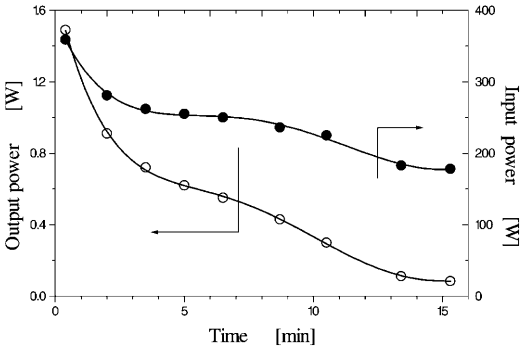

Fig. 3. Temporal behavior of output power of the laser with Al electrodes. Scheme of type 1

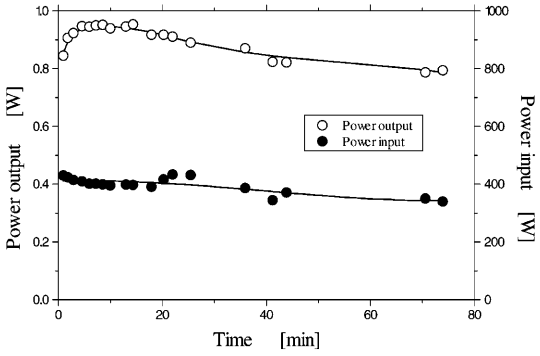

Fig. 4. Temporal behavior of output power of the laser with Pyrex slab. Scheme of type 2. Excitation frequency 120 MHz

at the start of the laser operation, but after a few minutes the input electrical power drops, an indication that the plasma impedance changes. It seems reasonable that such behavior may be the result of a change in the electrode surface properties [9], contamination of the gas mixture by sputtering products of the electrodes, or by poisonous gases as the result of a leak. The first two reasons directly depend on the electrode material and its preliminary processing. The last reason seems to be of less significance because the vacuum of the system before its filling was high and stable. It can however not be ignored, since the laser parameters have demonstrated to be sensitive with respect to the initial vacuum treatment. The best peak output power was obtained after several hours (usually more than 2 h) of pre-pumping of the laser chamber. Despite the fact that the vacuum was usually good enough after about one hour of pumping, the peak output power after 1 h of pumping was normally two times lower than the output power after more than 2 h of pumping.

We performed experiments with copper electrodes of 12 mm width and an inter-electrode gap between them of 4 mm. The temporal behavior of the output power generally has the same features as the above described results for Al electrodes, except for a two times longer degradation time when using copper electrodes.

These results show that the most probable reason for degradation of the laser output is a modification of the electrode surfaces by the active plasma. This results in the appearance of particles on the surfaces, which can be desorbed into plasma. Such processes might be attributed to diffusion-like transfer of contaminates from the bulk of the plasma to the surface of the metal. The desorption of particles from the surface into the vacuum takes place during the observation time.

2.2 Dielectric envelope

In Fig. 4 the temporal behavior of the input power and output power of a laser with a Pyrex dielectric envelope of rectangular cross-section are shown. In this experiment the temporal behavior of the laser output is essentially more stable compared to the above case of metal electrodes. The dependencies for quartz and Pyrex envelopes with circular cross-sections were practically the same as shown in Fig. 4 within the experimental errors.

In contrast to the quartz and Pyrex envelopes, the temporal behavior of the laser parameters with an Al_2O_3 circular envelope was very close to that with pure metal electrodes. The initial peak output power in this case was close to that measured with circular Pyrex and quartz envelopes, but after about 5 min the output power was 2 to 3 times lower. The only difference between the metal electrode laser and the Al_2O_3 envelope is the time scale. The laser with Al_2O_3 envelope has a peak power duration that is roughly 1.5 times longer than the laser with Al electrodes (Fig. 3). It is reasonable to assume that the behavior is again determined by the processes mentioned above.

It is important to note that in all cases mentioned above, both for metallic and dielectric electrodes, a common feature can be observed. In all cases, at the beginning of the operation, the visible emission of the discharge has the inter-electrode space structure with a bright central region, typical for the high-current γ-type rf discharge [10]. During operation this structure changes gradually to that typical for the low-current α-type rf discharge. This evolution is accompanied by a change of the discharge impedance and a decrease of the laser output power. These processes are much slower for pure dielectric materials (Pyrex, quartz) than for metallic Al and Cu electrodes and for the metal-containing ceramic Al_2O_3.

2.3 Welded system

This type of laser head demonstrates the most promising results. The tests have been performed for an operational time of up to 100 h and they showed a very stable level of laser

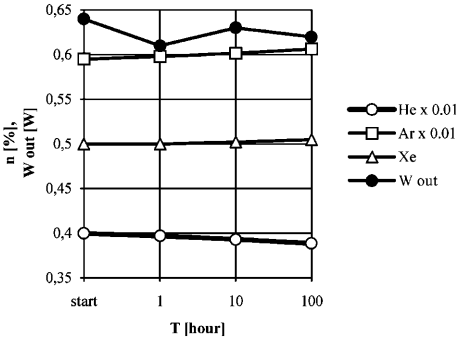

Fig. 5. The relative concentration of the laser gas mixture compositions and output power as a function of the working time

output power (Fig. 5). The same figure illustrates also the temporal behavior of the gas mixture components. It shows that the chemical composition is quite stable.

The gas analysis also shows that the densities of the additional components (H_2, H_2O, etc.) are negligible and they remain at the same level both after the vacuum-heat treatment (see Sect. 2.3) and during operation time. It means that the preliminary vacuum, combined with the heat processing, prevent the desorption of such contaminants. On the other hand the absorption of initial rare gas components itself is essential.

3 Conclusion

A series of lifetime tests for the atomic Xe laser with rf excitation have been performed for the first time to elucidate the possibilities of long-term sealed-off operation.

Experiments with metal electrodes and metal-containing ceramic electrodes, without special processing apart from the vacuum treatment, show very short operation times of the order of a few minutes. Longer operation times, in the order of a few hours, are demonstrated for discharges in metal-free dielectric envelopes. Real long-term operation of more than 100 h is possible by using specially processed covar electrodes in combination with hard sealing technologies. These technologies are well elaborated in the electrovacuum industry, ensuring these rf-excited lasers have good prospects as long-term operating sealed-off devices. In contrast to low-pressure dc lasers, the Xe atom "burning out" effect is not pronounced.

The experiments described lead to the assumption that the important reasons for laser degradation are the influence of the contaminants on the conditions for the transition from γ to α discharge types combined with the fact that for the rf-excited atomic xenon laser a γ-type discharge is more suitable for lasing.

The advantage of covar electrodes over the investigated metal or dielectric envelope ones can probably also be attributed to the Ni component in this alloy. It is known that Ni decreases the cathode fall voltage compared to Cu electrodes [10], thus reducing the particles´ desorption from the electrodes due to the ionic bombardment. According to Raizer et al. [10], the impact of Ar^+ on electrodes produced from Al, Cu, and Mg results in microstructure changes on the working electrodes surface. Simultaneously we observe an increase of the autoelectron current from these surfaces of about 2 to 10 times. When Ni, Mo, Ti, Ta, or W electrodes are used in the discharge, any visible changes of the plasma discharge after a long period of laser operation are absent.

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