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Double XeCl Laser with Lateral UV Preionization

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Abstract. We present a very compact and very reliable laser system formed of two discharge sections both with lateral UV preionization. The discharge electrodes are contained in a single vessel and form an oscillator-amplifier system. A single spark gap switches on both circuits. By applying a generalized self-filtering unstable resonator to the oscillator and injecting the laser beam into the single pass amplifier, an output beam of 105 mJ, with a brightness of 5.5×10^{13} W cm^{-2} Sr^{-1} has been obtained. Moreover, by applying a pulse-forming network in one discharging circuit, the duration of the discharge breakdown has been increased and output laser pulses of 40 ns FWHM, and 80 ns base width duration (at 10% points) and of energy 100 mJ are obtained.

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Rare gas halide lasers of high power and low beam divergence are of particular importance in many applications such as photolitography [1], material processing [2], non-linear optics [3], laser radar and surgical medicine [4]. To obtain a laser beam of high energy and good optical quality, i.e. low divergence and uniform cross-section intensity, oscillator-amplifier laser system have been developed [5, 6].

It has been observed that the laser beam characteristics are strongly dependent on the uniformity of the laser discharge. In turn, the discharge uniformity strongly depends on the preionization of the gas mixture [7]. Excimer lasers with X-ray preionization produce high energy and good optical quality beams, but their high costs, large volume and radiation safety problems inhibit the widespread use of these devices. Capacitor discharge systems with UV preionization are much simpler to build and to manage [8], and can also provide quite uniform discharges. In particular, it has been shown that, with the UV preionization placed laterally to the discharge electrodes, a more uniform discharge can be obtained than is obtained with the UV preionization placed behind a drilled discharge electrode [8]. In this last preionization system a high preionization gradient near to the drilled discharge electrode is present.

In this paper we present a very compact and very reliable laser system formed by two capacitor discharge sections both with lateral UV preionization. Both discharge sections are contained in a single vessel and act as an oscillator-amplifier system.

This technique is generally used to get high energy and high optical quality laser beams. The oscillator can be equipped with an unstable cavity to obtain low-power high-optical quality laser radiation and, in order to amplify it, the oscillator pulse is injected into the amplifier. During our experiments a generalized self-filtering unstable resonator (GSFUR) has been applied to the oscillator and the experimental results have been compared with those obtained with another laser having the same unstable cavity but with a UV preionization placed behind a drilled discharge electrode.

Measurements of the amplifier output energy as a function of the input beam energy have been carried out, and the small signal gain and the saturation power density of the amplifier module have been determined.

Finally, a pulse-forming network has been applied to one discharge section equipped with a plane-parallel cavity. This scheme allows one to vary the breakdown voltage and the laser pulse duration.

Experimental Apparatus and Results

Our laser system consists of two discharge sections, placed in a PVC tube, 20 cm in diameter and 68 cm long.

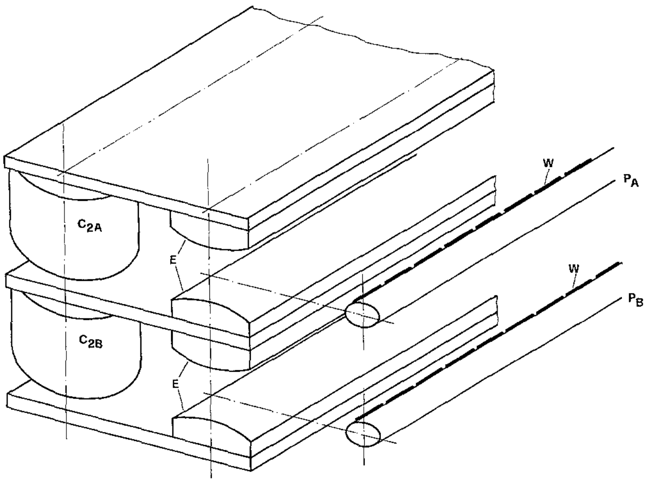

Fig. 1. Laser cross section. C_{2A}: discharging capacitors of Sect. A; C_2: discharging capacitor of Sect. B; E: electrodes; P_A: preionization rod of Sect. A; P_B: preionization rod of Sect. B

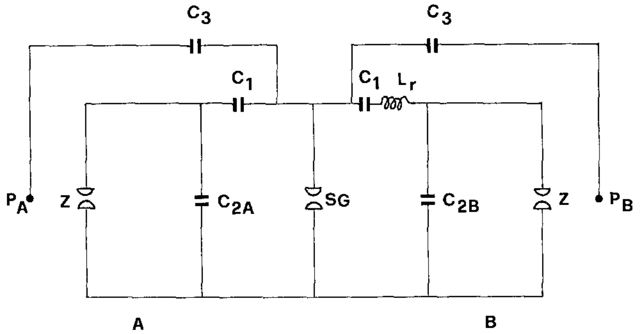

Fig. 2. Circuit diagram. $C_1 = 90$ nF: charging capacitors; $C_{2A} = 25$ nF: discharging capacitors of Sect. A; $C_{2B} = 25$ nF: discharging capacitor of Sect. B; $C_3 = 10$ nF: preionization discharging capacitor; L_r: inductor; SG: spark gap; Z: laser impedance

Each discharge section is formed of two 50 cm long brass electrodes, with an inter-electrode gap 2 cm wide, of 10 ceramic capacitors, which form the discharge capacitance of 25 nF, and of the UV preionizer. The preionizers are placed laterally to the electrodes, at 60 mm from them in order to illuminate the discharge volume and to exclude the use of drilled electrodes. A view of our laser system is shown in Fig. 1. Each preionizer is formed by an alumine rod with 43 tungsten pins (W in Fig. 1) aligned on the external diameter of the rod. The pins are 11 mm long and form 42 gaps 1 mm wide and are energized by the capacitor $C_3 = 10$ nF which is charged at the same charging voltage as the C_1 capacitors.

Both discharge sections end with two quartz windows placed at the Brewster angle.

The discharging capacitors C_{2A} of Sect. A, and C_{2B} of Sect. B, are fed by two charge-transfer circuits both with a capacitance $C_1 = 90$ nF and an inductance of 1700 nH, given by the electrical wirings. In the circuit of Sect. B (amplifier), we introduce a coil of inductance $L_r = 100$ nH in order to get a 12 ns delay between the discharges. The circuit diagram is outlined in Fig. 2.

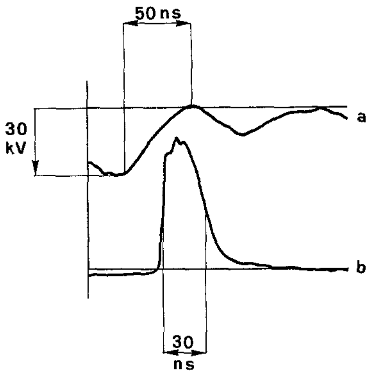

Fig. 3. Evolution time of the breakdown voltage intensity measured on Z (a) and of the laser pulse (b)

A trigger signal leads the single spark gap (SG) of the double circuit. It is thus possible to get a good discharge synchronization of the two laser sections.

It is important to point out that synchronization problems due to the gas degradation, which arise in two operating excimer lasers, can be overcome when the same gas mixture is used in both sections [9]. During our experiments the discharge chamber was filled with a 0.1% HCl, 2.4% He, 1.7% Xe, and 95.8% Ne mixture at a total pressure of 350 kPa.

First, we tested the behaviour of each module by using an optical cavity formed by an aluminized plane mirror as total reflector and a quartz disc as output coupling mirror. With a charging voltage of 40 kV, we have obtained a laser beam of 2×1 cm^2 centred between the electrodes, of 100 mJ, 30 ns (FWHM) pulse length, and 5 mrad divergence at the wavelength of 308 nm. Under these experimental conditions, the duration of the discharge voltage is estimated to be 50 ns, as can be observed from the discharge voltage time history. Figure 3 shows the waveforms of discharge voltage measured between the electrodes and the output laser pulse.

The two discharge modules were coupled to realize an oscillator-amplifier system to yield a high energy, high optical quality laser beam. A generalized self-filtering unstable resonator (GSFUR) [10, 11] was applied to the oscillator and the output beam from the oscillator was injected into the single pass amplifier.

The GSFUR is formed by a concave mirror M_2 with focal length f_2, a plane mirror M_1 and a field limiting aperture (AC) of radius r, placed at distances L_1 and L_2 from M_1 and M_2, respectively.

The AC radius is given by the following relation:

$$r \simeq (L_2 \lambda / 2)^{1/2}, \tag{1}$$

where λ is the wavelength of the laser. The magnification M of the cavity is;

$$M \simeq -2L_1/L_2 . \tag{2}$$

Since in this cavity the mode wavefront is curved, the output beam can be collimated by a mirror M_3 having a focal length

$$f_3 \simeq d + 2L_1 , \tag{3}$$

where d is the distance between AC and M_3.

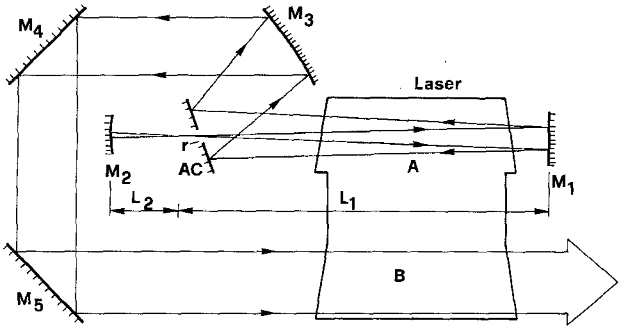

Fig. 4. Experimental set up. $L_2=27.5$ cm, $L_1=122.5$ cm

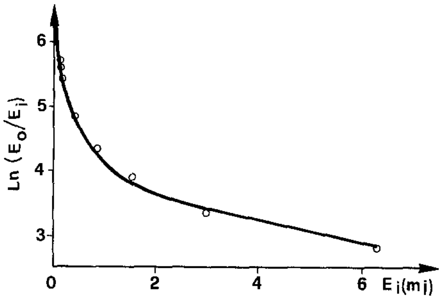

Fig. 5. Behaviour of $\ln(E_o/E_i)$ vs E_i. (o): experimental points. Full line: plot of expression (5)

In particular we have realized a GSFUR of magnification $M=-10$. It is formed by an aluminized plane mirror M_1 and a concave mirror M_2 with focal length $f_2=25$ cm. The distance between the mirrors is 150 cm. An aluminized plane mirror with a central hole of 0.4 mm diameter placed at 27.5 cm from M_2 was used as limiting aperture and as output coupler (AC). The AC is tilted a few degrees with respect to the resonator axis. In order to collimate the output beam, we used an aluminized concave mirror M_3 of focal length $f_3=250$ cm, placed at 5 cm from AC. Figure 4 shows the experimental set up.

With this unstable cavity applied to the oscillator, an output beam of 13 mJ with a pulse length of 24 ns (FWHM) was obtained. The beam diameter on M_3 is 6 mm, while the beam divergence is 0.24 mrad. The divergence is only 1.2 times the diffraction limited value which is $1.22\,\lambda/|Mr|$.

When the same GSFUR cavity was applied to an excimer laser having the same gain region length but a UV preionization placed behind a drilled discharge electrode [8], an output laser beam of low optical quality was obtained. In fact, a sufficient number of filaments were present in the discharge region and the beam divergence was 2.8 and 3.2 mrad parallel and perpendicular to the electric field direction, respectively. These divergence values are higher than those achieved from the oscillator with the preionization placed laterally to the electrodes, and could be due to the high preionization gradient near to the drilled discharge electrode.

As recorded in [11], to get an output beam of low divergence from a laser having a drilled electrode, a lower operating pressure and a lower charging voltage (220 kPa, 30 kV) was used and a lower output energy was obtained. Under these experimental conditions an output beam of 3.5 mJ with a divergence of 0.26 mrad was achieved.

By using two plane mirrors M_4 and M_5 as shown on Fig. 4, the output beam from the oscillator was directed into the amplifier section. From the amplifier we obtained an output laser beam of 105 mJ per pulse, with a divergence of 0.9 mrad and a brightness of 5.5×10^{13} W cm^{-2} Sr^{-1}.

To study the behaviour of the amplifying section, we measured the output beam energy as a function of the input beam energy. Variation of the input beam energy was achieved by using neutral density filters placed on the optical path of the beam before its injection into the amplifier. The experimental results are shown in Fig. 5.

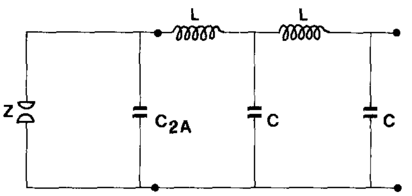

Fig. 6. Circuit of the PFN connected to the C_{2A} capacitor. $C=10.2$ nF; $L=6.3$ nH; Z: laser impedance

When a stationary model is used to describe the amplification of a lasing system, it turns out that [12]

$$\ln(E_o/E_i)=gl-(E_o-E_i)/E_s\,, \tag{4}$$

where E_o, E_i, and E_s are the output energy, the input energy and the saturation energy, respectively; g is the small signal gain and l is the active length of the laser discharge.

By interpolating our experimental results using (4), as shown in Fig. 5, we obtained $g=0.135$ cm^{-1} and $E_s=25$ mJ. As a consequence, the saturation power density is 3.7 MW/cm^2. These results are in good agreement with those obtained by other authors, with different techniques, in XeCl laser systems with UV preionization [13].

Moreover, a pulse-forming network (PFN) having a total delay time of about 18 ns was connected to the C_{2A} capacitor in order to get longer laser pulses as required in many applications of excimer lasers. For example, to get a laser pulse having a narrow linewidth, high dispersion elements are inserted into the cavity and the use of longer laser pulses increases the round trip number which produces a narrower linewidth.

Figure 6 shows the scheme of PFN connected to the C_{2A}. The PFN is formed of two cells both containing 6 UHV −12 A TDK capacitors of 1.7 nF connected in parallel, and 6 independent inductors of 38 nH each, also connected in parallel. With these values of capacitance and of inductance, the calculated PFN characteristic impedance is 0.9 Ω. This value is close to the measured plasma average impedance of the laser discharge [14]. When the ideal conditions are satisfied, i.e. load impedance equal to PFN characteristic impedance, one can show that the PFN discharge time must be

$$\tau=4(CL)^{1/2}=32\text{ ns}\,, \tag{5}$$

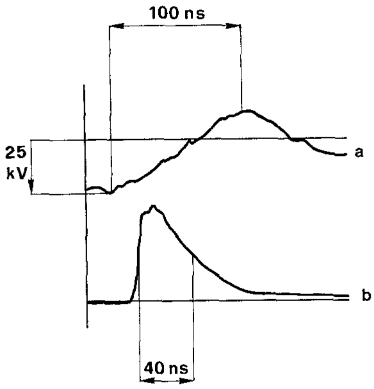

Fig. 7. Evolution time of the breakdown voltage intensity (*a*) measured on *Z* and of the laser pulse (*b*) with the PFN connected to the C_{2A} capacitor

where $C = 10.2$ nF is the total capacitance of a cell and $L = 6.3$ nH is the total inductance of a cell.

Under these experimental conditions, and leaving the charge transfer circuit unchanged, a charging voltage of 40 kV produced laser output of 100 mJ and 40 ns FWHM and 80 ns base width (at 10% points). The laser pulse and the breakdown voltage time evolution are shown in Fig. 7.

By comparing Figs. 3 and 7, it can be seen that the time duration of the breakdown voltage of Fig. 7 is 50 ns longer than the breakdown voltage time duration shown in Fig. 3. The larger increase of the breakdown voltage time duration (50 ns) with respect to the expected value (32 ns) is attributed to the plasma impedance time evolution which can be approximated by an exponential function [15]; then, after a few nanoseconds its value is probably smaller than the PFN characteristic impedance value (0.9 Ω). This observation is also confirmed from Fig. 7 where the breakdown voltage changes polarity about 70 ns after the discharge onset, thus justifying a plasma impedance lower than the characteristic impedance.

It is important to observe that the breakdown voltage intensity is 30 kV in Fig. 3 and 25 kV in Fig. 7.

Although the time duration and the discharge voltage intensity are different in the two experimental conditions investigated and shown in Figs. 3 and 7, the laser action always starts 20 ns after the discharge onset. As can be seen from Fig. 7, the laser pulse duration is increased by about 10 ns while the duration of the breakdown voltage is about 50 ns longer. Probably, in this last experiment, the shortening of the laser impedance does not allow a good energy coupling efficiency from PFN to laser mixture.

The duration of the output pulses is also dependent on the partial pressure of HCl [16]. In particular, the decreasing of the HCl partial pressure within the laser gas mixture yields a longer output pulse and a lower output energy. We did not investigate it because this last method reduces the laser gain which is very important for many applications.

Conclusions

An efficient double XeCl laser in the configuration of oscillator-amplifier using a GSFUR cavity in the oscillator section has been demonstrated. A maximum output energy of 105 mJ and a brightness of 5.5×10^{13} W cm^{-2} Sr^{-1} was obtained.

To the best of our knowledge, this is the first oscillator-amplifier system to use a GSFUR as unstable resonator applied to the oscillator.

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