Red-F* Laser and VUV-F_2 Emission Pumped at Low Pressure by Longitudinal, Lamp-Like Discharge

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Red-fluorine-atom (Red-F*) laser oscillation (λ = 630-780 nm) and strong fluorescence of VUV-F_2 emission (λ = 157 nm) are observed in a lamp-like discharge in a longitudinal discharge excitation tube. The laser tube consists of a 30 cm long Pyrex glass pipe with an inner diameter of 2 mm, and a step-up transformer coupled directly to the discharge tube without a high-voltage switch. Excitation is produced by wall-coupled discharge. The laser pulse width is 6.1 ns at 100 Torr (13.3 kPa, with an F_2 concentration of 5 %) when a slow-rising voltage pulse of −40 kV (rise time: 253 ns) is applied. VUV-F_2 emission of a 24.5 ns (FWHM) pulse width was generated simultaneously with the red-F* laser.

Keywords: gas laser, red-F* laser, VUV-F_2 emission, excimer lamp, wall-coupled discharge, longitudinal excitation

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1. Introduction

In general, it is considered that an excimer laser does not oscillate from the discharge of an excimer lamp because the laser's discharge and excitation mechanisms are different from that of the excimer lamp. The lamp, which uses dielectric barrier discharge (DBD), is excited by a slow-rising AC voltage, which is directly applied to the discharge tube [1]. On the other hand, the laser requires a fast discharge, driven by a low-inductance circuit, such as a capacitor-transfer circuit, with a fast-rising switch [2–4].

We have recently developed a longitudinally excited N_2 laser (λ = 337 nm) with an excitation circuit similar to that of a DBD lamp [5]. Results show that laser oscillation is possible even if we use the lamp discharge.

A longitudinal discharge excitation scheme is different from a transverse discharge excitation scheme used in commercially produced excimer lasers, and involves excitation discharge in the direction of the laser axis [4, 5]. This scheme can sustain a high breakdown voltage, even under low gas pressures, because of its long electrode gap. But this scheme emits low output energy, because the discharge impedance is large and the discharge current is small. This device does not need a high-pressure vessel and is small and inexpensive. Low-pressure discharge produces a fast electron drift velocity, and generates uniform discharge without preionization. In addition, when the discharge length is long and cross-section is small, a uniform discharge occurs, even if there are residual charges in the discharge tube after the previous discharge. The uniform discharge is assumed to be a cluster of minute spark discharges, distributed uniformly (diffuse streamer discharge).

Previously, we developed a longitudinally excited VUV-F_2 laser (λ = 157 nm) with a fast discharge, using a capacitor-transfer circuit at low pressure [4]. However, in the VUV-F_2, laser oscillation at low pressure, the red-F* laser (λ = 630-780 nm), which oscillates by transverse discharge excitation scheme at high pressure [3, 4], did not oscillate.

In this work, we observed red-F* laser oscillation using a system that combines a longitudinal discharge tube with the same dielectric barrier discharge as in the lamp. A strong VUV-F_2 emission was observed, with the same timing as the red-F* laser.

2. Experimental Set-Up

The laser system is shown in Fig. 1. The laser tube is made of a Pyrex glass pipe with an inner diameter of 2 mm, an outer diameter of 7 mm, and a length of 30 cm. The center of the laser tube is covered with an Al foil of 10 cm length, which serves as a wall coupling electrode. Two metallic electrodes, which serve as mirror folders are attached to the ends of the glass tube and connected to ground. An optical cavity is formed by a CaF_2-coated Al mirror and a CaF_2 window. In this experiment a pulsed power supply is used instead of the AC power supply, which is used in the lamp. A −600 V primary voltage pulse is generated from the power supply with a silicon-controlled rectifier. The voltage pulse is fed to a step-up transformer (EG&G TR-153 with a primary capacitance of 0.22 μF) and applied to the Al foil. The coaxial capaci-

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tance, consisting of the Al foil, glass tube, and ionized gas, is estimated to be 21.3 pF. When the voltage reaches the breakdown threshold, the discharge takes place longitudinally along the wall of the laser tube.

This laser device has the same excitation circuit as a lamp: it has no fast-rising switch, but has large inductance caused by direct connection of the transformer to the laser tube and used wall-coupled discharge.

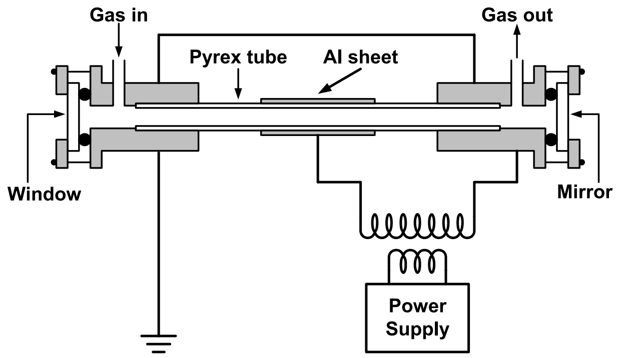
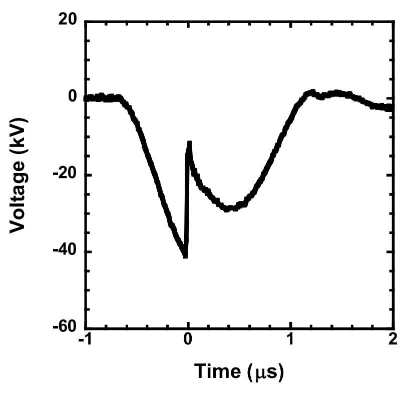


Fig. 1 Schematic diagram of the laser system.

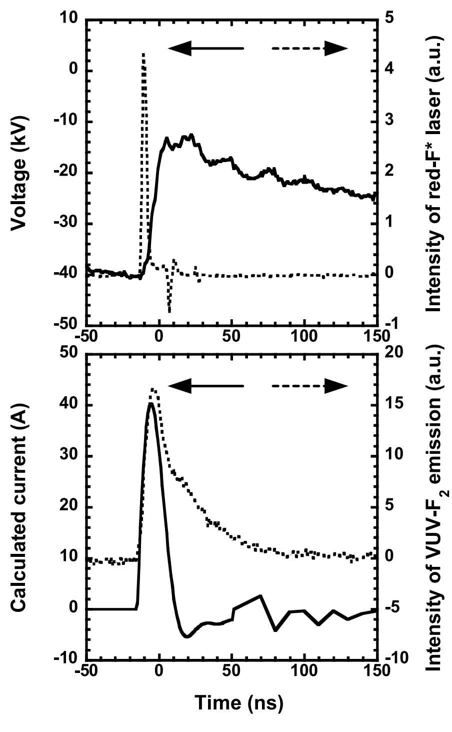
3. Experimental Results

The waveform of a red-F* laser pulse was measured with a high-speed photodiode (Hamamatsu, R1328U-01). The VUV-F_2 emission pulse waveform was obtained with a N_2 purge of the optical path, and was measured with a high-speed VUV-photodiode (Hamamatsu, R1328U-54); the waveform of the applied voltage to the wall coupled capacitance was measured with a high-voltage probe (Tektronix, P6015A).

Figure 2 shows waveforms of the applied voltage, the red-F* laser pulse, the VUV-F_2 emission pulse, and the calculated discharge current in a 100 Torr (13.3 kPa) He/F_2 gas mixture (F_2 concentration of 5 %). The discharge current was simply calculated by the temporal differentiation of the applied voltage, because the excitation circuit is a series circuit of the wall-coupled storage capacitance and the impedance of the discharge space. The applied voltage reached −40 kV, with a rise time of 253 ns, after which the discharge began. The voltage dropped by almost −11 kV within 12 ns. This voltage drop was caused by the main discharge — the discharge current began with the start of discharge. The maximum value and the pulse width of the discharge current were 41.0 A and 8.4 ns (FWHM), respec-

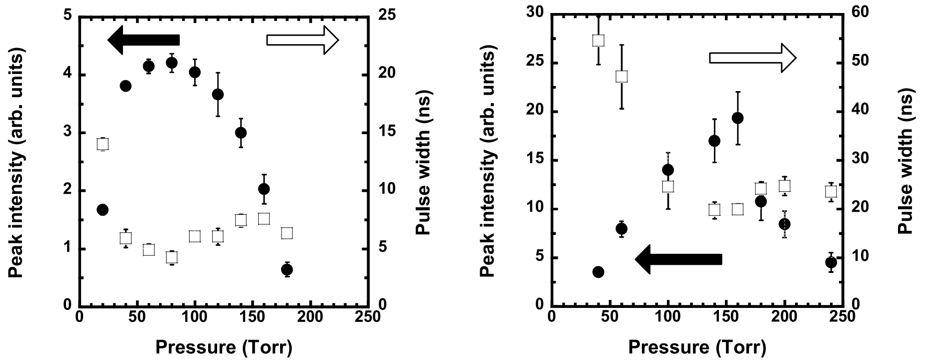


(a)



(b)

Fig. 2 Waveforms of the applied voltage, red-F* laser pulse, VUV-F_2 emission pulse, and the discharge current at 100 Torr (F_2: 5 %). (a) Overall waveform of the applied voltage. (b) Magnified time scale figure of the laser pulse. In the above figure, the solid and broken lines are the red-F* laser pulse waveform and applied voltage waveform, respectively. The solid and broken lines in the lower figure are the calculated discharge current waveform and VUV-F_2 emission pulse, respectively. The vertical axes are indicated by solid and dotted arrows.



(a) (b)

Fig. 3 Dependence of the output characteristics of the red-F* laser and VUV-F_2 emission on total pressure (F_2: 5 %). (a) Red-F* laser. (b) VUV-F_2 emission. Circles and squares indicate the peak intensity and pulse width, respectively; their vertical axes are indicated by black and white arrows. Error bars indicate standard deviation.

tively. The large impedance of the excitation circuit caused an incomplete voltage drop (local maximum value was 24.5 ns, pulse width (FWHM) of 813.6 ns, and fall time of 477.7 ns), but this current was much smaller than the main discharge current, at 76.8 mA (pulse width: 430.3 ns). The red-F* laser started with the start of discharge, and its pulse width was 6.1 ns (FWHM). The VUV-F_2 emission started with the start of discharge, which was simultaneous with the red-F* laser. The rising-edge waveform of the VUV-F_2 emission was the same as that of the calculated discharge current. The pulse width, and the rise and the fall time of the VUV-F_2 emission were 24.5 ns (FWHM), 5.8 ns, and 40.6 ns, respectively. Figure 3 shows the dependence of the red-F* laser and the VUV-F_2 emission characteristics on gas pressure. The red-F* laser output intensity reached a maximum at a pressure of 80 Torr (11 kPa); the laser pulse width had a minimum value of 4.2 ns at the same pressure. The output intensity of the VUV-F_2 emission reached a maximum at a pressure of 160 Torr (21 kPa); the emission pulse width had a minimum value of 19.8 ns at this pressure.

4. Discussion and Conclusion

We developed a longitudinally excited red-F* laser with the same excitation circuit as an excimer lamp: it had no switch, the transformer was connected directly to the laser tube, and used wall-coupled discharge (DBD). VUV-F_2 emission was observed from the start of the discharge, simultaneous with the red-F* laser.

It is well known that the pumping mechanism of the red-F* laser is the dissociative excitation given by

$$He^* + F_2 \rightarrow F^* + F + He.$$

According to the references [3, 6–8], the rate constant of this reaction is slow (8.2×10^{-30} cm^6/s). This reaction does not explain the fast-rising red-F* laser observed at the start of the discharge. Hence, it is possible that F* was formed by a reaction that was faster than the dissociative excitation, for example, the fast-rising direct excitation of electron recombination,

$$F_2^+ + e \rightarrow F^* + F$$

(7.0×10^{-8} cm^3/s, according to the references) [7, 8]. F* (^{2}P, ^{4}P), whish is generated by reactions, including the red-F* laser transition, is a precursor of the generation of F_2^* (D') —the upper level of VUV-F_2 in the neutral reaction [3, 6–9].

In addition, the fast-rising VUV-F_2 emission that was observed with the start of discharge, simultaneous with the red-F* laser in this work, is generated by a different excitation than that given in previous reports [3, 7]. In the transverse discharge excitation scheme at high pressure, the ion channel reaction

$$F^- + F^+ + He \rightarrow F_2^*(D') + He$$

is assumed to be the dominant process leading to the production of F_2^* (D') [3]. In the longitudinal discharge excitation scheme at low pressures (He/F_2 mixture with a gas pressure of 40 Torr (5.3 kPa), an F_2 concentration of 1.5 %, and excitation density of 2.3 MW/cm^3), it has been thought that the direct excitation of electrons

$$F_2 + e \rightarrow F_2^*(D') + e$$

is dominant, because the gain rises with the start of discharge, as with a N_2 laser, and the red-F* laser does not oscillate, even if the excitation density is six times higher than that involved in this work [4]. Here, (He/F_2 mixture gas at a pressure of 100 Torr, with F_2 concentration of 5 %, excitation density of 429 kW/cm^3, and a discharge volume of 0.94 cm^3), the neutral channel that uses F^* as the precursor

$$F_2 + F^* \rightarrow F_2^*(D') + F$$

is dominant, because the VUV-F_2 emission (rise time of 5.8 ns and pulse width of 24.5 ns) coincides with the start of discharge, simultaneous with the red-F^* laser. However, the neutral channel is also dominant in VUV-F_2 emission pumped by microwave discharge at high pressures and large volume (He/F_2 gas at a pressure of 300 Torr (40 kPa), with an F_2 concentration of 5 %, discharge volume of 14.13 cm^3, and a microwave frequency of 2.45 MHz), but the emission characteristics differ from that of this work, and the calculated time history of the VUV-F_2 emission is very slow (rise time of 54.9 ns and pulse width of 177.4 ns) [8]. In this work, the reason for the fast-rising VUV-F_2 emission to began at the onset of discharge is due to both the fast generation of F^* by the fast-rising red-F^* laser, and the effect of the discharge tube's inner wall on the excitation reaction and the collision reaction with the inner wall [10]. In this work, the mean free path is long, and the surface area of the inner wall of the discharge tube is large, because of the wall-coupled discharge in the longitudinal discharge tube at low pressures. Therefore, the inner wall has an effect on the excitation reaction and the collision reaction with it

$$F_2 + F^* + \mathrm{Wall} \rightarrow F_2^*(D') + F$$

may occur fast. The same effect may apply to the production of F^*. Therefore, excitation reactions of this discharge system are different from those of previous systems.

In this experiment, we do not obtain VUV-F_2 laser oscillation because the cavity is not good for VUV, and the input excitation power is limited by the wall-coupled storage capacitance. By improving these points, the VUV-F_2 laser is expected to oscillate enough, even by the same system as the lamp.

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