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Gain and Saturation Measurements in a Discharge Excited F_2 Laser Using an Oscillator Amplifier Configuration

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Abstract. The small-signal gain coefficient and the saturation intensity of a F_2 pulsed discharge molecular laser at 157 nm have been measured using two discharge devices in an oscillator-amplifier configuration. The small signal gain coefficient was measured to be $5.2 \pm 0.4\%\ \mathrm{cm}^{-1}$ at 3 atm total pressure and 1.5 cm electrode spacing and $4.1 \pm 0.4\%\ \mathrm{cm}^{-1}$ at 2 atm total pressure and 2 cm electrode spacing while the values of the saturation intensity were 5 $\mathrm{MW/cm}^2$ and 4.6 $\mathrm{MW/cm}^2$, respectively.

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The laser transition $3\Pi_2 g \rightarrow 3\Pi_2 u$ of the molecular fluorine provides a strong monochromatic radiation source in the V-UV region of the spectrum [1–3] useful for photochemical applications [4–7]. It has been reported recently [8] that the value of the output energy from a pulsed discharge molecular laser at 157 nm is of the order of 112 mJ per pulse at 8 atm total gas pressure. The performance of such a system depends on the small signal gain coefficient g of the $3\Pi_2 g \rightarrow 3\Pi_2 u$ transition and the absorption coefficient at this wavelength.

The small-signal gain coefficient for a pulsed discharge F_2 laser has been measured by Cefalas et al. [9] using the passive cell absorption method [10] at 2 atm total gas pressure and 2 cm electrode spacing and it was found to be $3.2\%\ \mathrm{cm}^{-1}$. This value is half than the one predicted by the theoretical calculations of Ohwa and Obara [11] considering only the dissociative collision of F_2 molecules by either ion-ion recombination or energy transfer reaction and neglecting the direct excitation of F_2 molecules by either electron impact or energy transfer from He*, He**, and He_2^*.

In this paper we report the measurement of the small-signal gain coefficient and the saturation intensity of a F_2 pulsed discharge molecular laser at 157 nm at 2 and 3 atm total gas pressure and 2 and 1.5 cm electrode spacing, respectively, using the oscillator-amplifier configuration method.

The values of the small signal gain coefficient were $5.2 \pm 0.4\%\ \mathrm{cm}^{-1}$ (3 atm, 1.5 cm electrode spacing) and $4.1 \pm 0.4\%\ \mathrm{cm}^{-1}$ (2 atm, 2 cm electrode spacing) [12] and the values of the saturation intensity were 5 and 4.6 $\mathrm{MW/cm}^2$, respectively.

1. Experimental

The experimental apparatus is shown in Figs. 1 and 2. It consists of two laser heads driven by discharge circuits of the charge transfer type [9, 13] which are triggered simultaneously by a spark gap switch. The two laser heads fire with a jitter of 1 ns at 28 kV charging voltage and they are loaded at the same total gas pressure of 2 and 3 atm.

When the spark gap fires the stored energy in the capacitors C_2 (=67.5 nF) is transfered into the discharge volume through the capacitors C_1. The double preionization of each laser volume (2 × 20 pins) ensures a uniform main discharge. The bronze nickel plated

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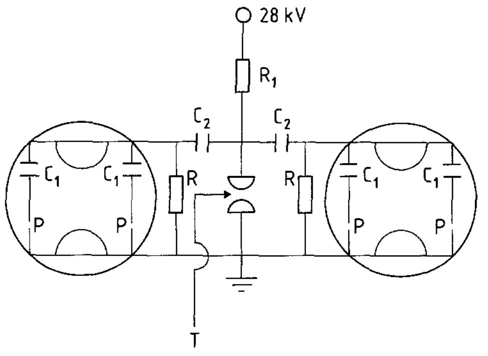

Fig. 1. Schematic lay out of the double discharge F_2 laser ($R_1 = 400\ \mathrm{k\Omega}$, $R = 500\ \Omega$, $C_2 = 25 \times 2.7$ nF, $C_1 = 20 \times 0.6$ nF, SG: Spark-gap, P: preionization pins)

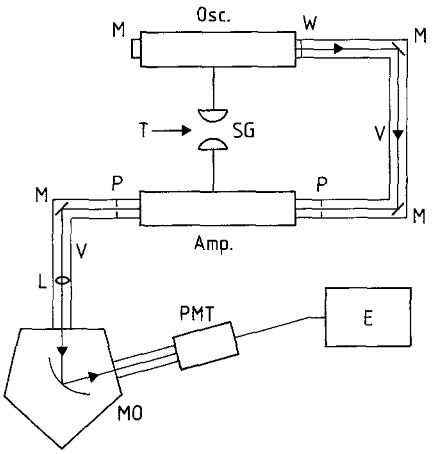

Fig. 2. Schematic lay out of the experimental apparatus for measuring the gain at 157 nm (Osc: oscillator, Amp: amplifier, M: mirror, P: pinhole, V: vacuum lines, W: LiF window used as output coupler of the oscillator, L: lens, PMT: photomultiplier, E: detection electronics)

electrodes were 60 cm long, 2 cm wide having hemispherical profiles with round surfaces and were placed 2 cm and 1.5 cm apart. The laser chambers were made of teflon tubes and were 100 cm long and 2 cm wide. The laser resonator consisted of a MgF_2 coated aluminum back reflector and a LiF output coupler. The signal was transmitted through stainless steel vacuum lines from the oscillator into the amplifier and from the amplifier to the monochromator while its amplitude was controlled by carefully letting the appropriate amount of air into the signal vacuum lines (Fig. 3). The signal was detected by a VUV monochromator (ACTON VM 502) having a resolution of 0.1 nm and a solar blind photomultiplier tube (EMIRIFI-821FV) connected to a Tektronix 7104 fast oscilloscope. The small signal gain coefficient g and the saturation energy E_s has been calculated by fitting the experimental results to [14, 15].

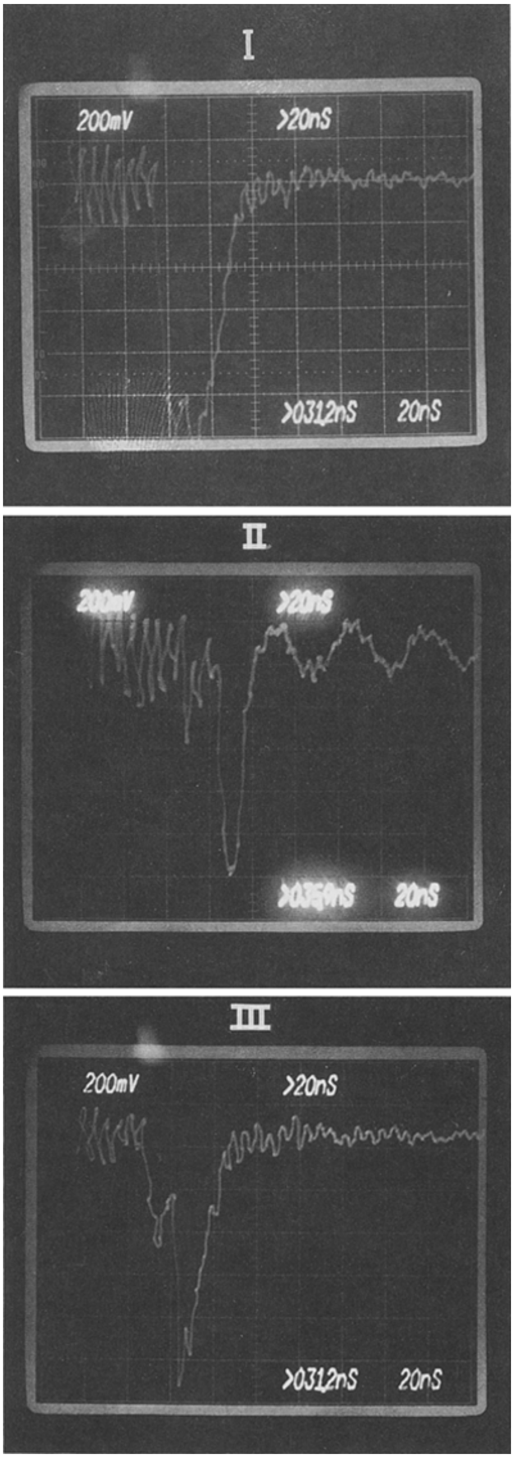

Fig. 3. I. Fluorescence signal at 157 nm; **II.** Input laser pulse; **III.** Amplified laser pulse

$$E_0 = E_s \ln\{1 + \exp(g \cdot L)\,[\exp(E_i/E_s) - 1]\}\,, \tag{1}$$

where E_0 and E_i are the experimentally measured values of the output and input energy of the laser radiation from the amplifier. The energy was measured with a Gentec pyroelectric detector (ED 100A) calibrated at 193 nm. The maximum output energy from the oscillator at 2 atm total gas pressure and 2 cm electrode spacing was 10 mJ, and 12 mJ at 3 atm total gas pressure and 1.5 cm electrode spacing. In both cases the FWHM of the output pulse was 12 ns. To avoid the possibility that the laser action from the amplifier due to the relatively high gain coefficient might saturate the laser transition, the length of the discharge plasma of the amplifier was controlled by appropriately masking the electrodes of the amplifier. Under our experimental conditions the length of the discharge volume of the amplifier was empirically found to be 35 cm in order to avoid self-oscillation. In this case the amplifier was lasing only with the use of an external optical cavity consisting of a flat Al+MgF_2 coated mirror and a LiF output coupler.

The signal from the oscillator was injected into the amplifier with 2 mirrors (Fig. 2) and its cross section was controlled with a circular pinhole in the amplifier input, 3 mm in diameter. The output was focused with the appropriate LiF lenses and mirrors in the entrance of the VUV monochromator.

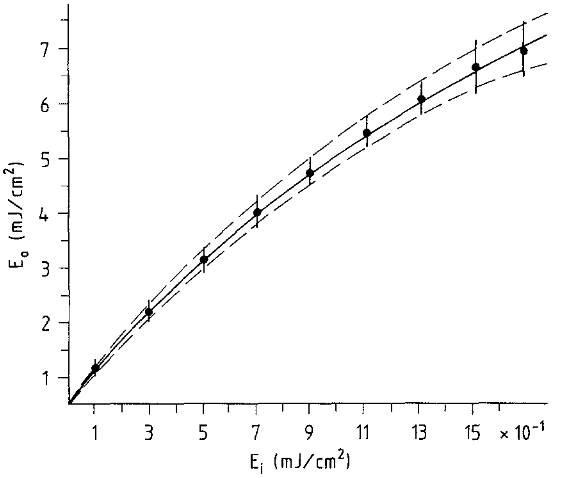

Fig. 4. Saturation curves of the amplifier at 28 kV charging voltage and 3 atm total gas pressure. The dashed lines have been calculated for $g=5.2\%\,\mathrm{cm}^{-1}$, $E_s=9\,\mathrm{mJ/cm}^2$ (upper) and 5 mJ/cm² (lower), respectively. The saturation intensity is 7 mJ/cm².

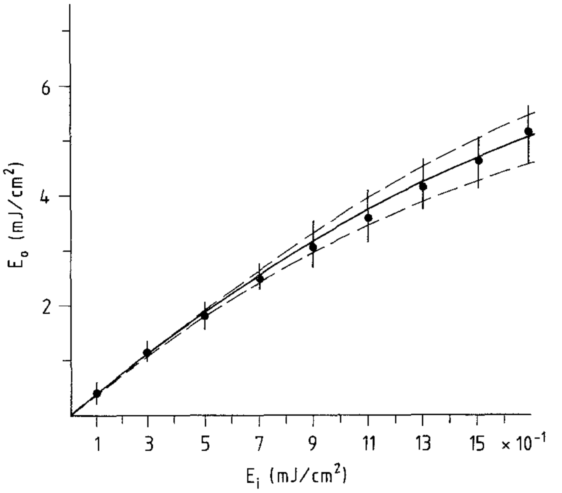

Fig. 5. Saturation curves of the amplifier at 28 kV charging voltage and 2 atm total gas pressure. The dashed lines have been calculated for $g=4.1\%\,\mathrm{cm}^{-1}$, $E_s=8\,\mathrm{mJ/cm}^2$ (upper) and 4 mJ/cm² (lower), respectively

2. Results and Discussion

In the case of amplification where the energy extraction from the amplifier, by the laser field of the oscillator, exceeds the rate of pumping of the laser level as it is determined by the plasma kinetics [15], (1) is valid.

When the pulse duration of the incident beam is much larger than the upper state lifetime t and shorter than the pumping pulse period t_p the amplifier operates under the steady-state condition [16]. In the case of no absorption the Rigrod equation [17] is valid:

$$l_n(I_0/I_i)=g\cdot L-(I_0-I_i)/I_s. \tag{2}$$

For our experimental conditions $\tau=12$ ns, $t=3.7$ ns [18], and $t_p=30$ ns, a value which has been deduced from the fluorescence spectra (Fig. 3) at FWHM and is in a good agreement with the theoretical predictions of Ohwa and Obara [11].

However, since the constant pumping time in Fig. 3 is 4 ns a value which is not much greater than the upper state lifetime and pulse duration, the validity of the steady state approximation (2) is not clear. By fitting the experimental results to (1) the saturation energy can be calculated to be 7 mJ/cm² (Fig. 4) for 3 atm total gas pressure and 1.5 cm electrode spacing, and 6 mJ/cm² for 2 atm total pressure and 2 cm electrode spacing. Taking into account the experimental errors the accuracy of our results was within 30% as it can be seen from the dashed curves of Figs. 4 and 5. The above experimental error was due to the lack of more experimental points at higher input energies because of the limitations which are imposed on the total output energy from our device (max 12 mJ). For a 12 ns laser pulse at FWHM the saturation intensity can be found to be 580 kW/cm² at 3 atm and 500 kW/cm² at 2 atm total gas pressure. The measured saturation intensity I_e is the effective saturation intensity [19] and it is related to the saturation intensity I_s of the corresponding laser transition through [19, 20]

$$I_e=(t/2\cdot\tau)\cdot I_s, \tag{3}$$

$$I_s=8\pi h\nu\tau_s\cdot\Delta\nu/\lambda^2\cdot t, \tag{4}$$

where t_s denotes the inverse transition probability for spontaneous emission at the operating wavelength, t is the lifetime of the upper laser level, τ is the pulse duration at FWHM, λ and ν are the operating wavelength and frequency of the laser transition, and $\Delta\nu$ is the bandwidth of the transition. Taking into account the experimentally measured values of the effective saturation intensity 580 and 500 kW/cm^2 at 3 and 2 atm total gas pressure, respectively, the pulse duration at FWHM of 12 ns and the lifetime of the upper laser level of 3.7 ns [18] the saturation intensities I_s are 3.8 and 3.2 MW/cm^2 at 3 and 2 atm of total gas pressure, respectively. This value is higher than the one calculated by (4) which is 400 kW/cm^2. This is the due to the ambiguity of the used theoretical approximation and corresponds rather to the type of the measuring equipment which is used [16]. By fitting the experimental results to (2), Fig. 7, the gain coefficient at 2 and 3 atm is 4.1 and 5.1% cm^{-1}. These values are the same as the ones which are taken by fitting the experimental results to (1). The saturation intensities are 11.2 and 11.6 mJ/cm^2 at 2 and 3 atm, respectively. These values are higher than the ones which have been taken by fitting the experimental results to (1). The small-signal gain coefficient can be measured accurately for injected energies up to 300 μJ/cm^2. The output energy from the amplifier E_0 versus the input energy E_i has a linear dependence (Fig. 6) and the experimental points are fitted to (5).

$$E_0=E_i\exp(g\cdot L). \tag{5}$$

The small-signal gain coefficient is a function of the pumping conditions of the laser levels and increases with increasing charging voltage, total gas pressure and reduced electrode spacing. The various experimental conditions under which the saturation intensity and the small-signal gain have been measured is summarized in Table 1. The saturation intensity and the small-signal gain coefficient of the F_2 molecular laser is comparable with the rest of the excimer lasers, a fact which suggests that higher energies can be ob-

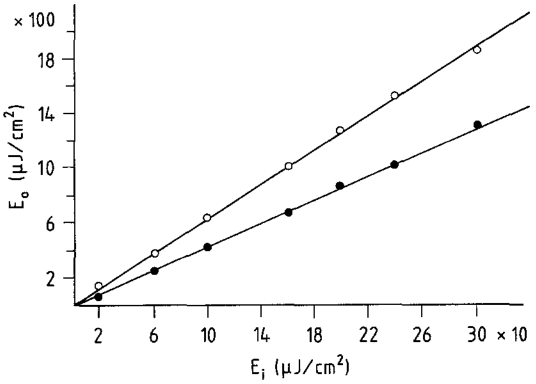

Fig. 6. Gain curves at low input energies at 3 atm total gas pressure and 1.5 cm electrode spacing ○ and 2 atm total gas pressure and 2 cm electrode spacing ●

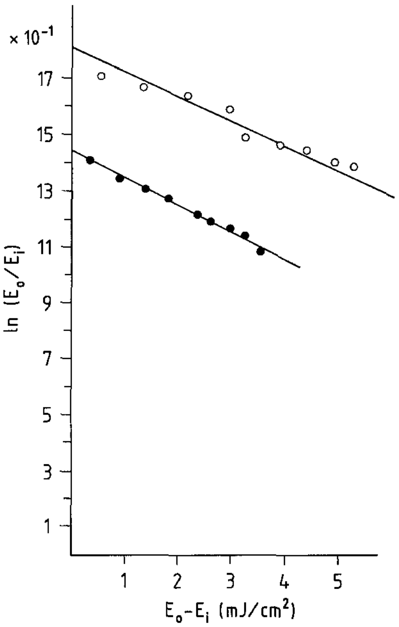

Fig. 7. Gain and saturation intensity curves fitted to (2) at 3 atm ○, and 2 atm ●, respectively

Table 1. Gain and saturation intensities of F_2 pulsed discharge molecular laser measured under various experimental conditions. E_L is the energy of the laser pulse and E_e is the total electric energy which is stored in the device ($1/2C_2V^2$)

Gain [% cm^{-1}]	I_s [MW/cm^2]	Method	Charging voltage V [kV]	Total gas pressure [Atm]	Overall efficiency E_L/E_e [%]	Ref.
3.2	–	Passive cell	22	2	0.01	[9]
4.1	5	Oscill.-Ampl.	28	2	0.03	This work
5.2	4.6	Oscill.-Ampl.	28	3	0.04	This work

tained from these devices assuming a better impedance matching between the pulse forming network (PFN) and the laser plasma [21]. The plasma discharge of a F_2 molecular laser runs into a stable discharge even in the presence of large field gradients between the electrodes due to the high values of the electron affinity of the F and F_2 ions [22, 23] and the relatively high value of the lifetime of the atomic fluorine negative ions with respect to the discharge duration time.

The amplifier laser pulse is shown in Fig. 3. There is some significant broadening in the tail of the pulse (40 ns), and mode competition effects between the 156.71 and 157.5 nm lines are shown in the amplified pulse. The above vibrational splitting of the transitions [2] is hardly seen in the fluorescence and laser temporal pulses of the oscillator. The spectrum analysis of the input and output pulses was limited by the resolution of our VUV monochromator of 0.5–1 Å.

3. Conclusion

We have measured the gain coefficient and the saturation intensity of a F_2 pulse discharge molecular laser using an oscillator and an amplifier which are triggered by a common spark gap switch. The gain coefficient was found to be 5.2% cm^{-1} at 3 atm total gas pressure and 1.5 cm electrode spacing at 28 kV charging voltage and 4.1% cm^{-1} at 2 atm total gas pressure and 2 cm electrode spacing at the same charging voltage.

The values of the saturation intensities were found to be 3.8 and 3.2 MW/cm^2 for the above experimental conditions, respectively, by fitting the experimental results to (1).

The saturation intensities were found to be 6 and 6.2 MW/cm^2 when we fitted our experimental points to (2) for each experimental case. The difference in the values of the saturation intensity for both cases is attributed rather to the invalidity of the existing amplification theories for the F_2 laser and the experimental error. The saturation intensities are considered to have values between the two extreme cases and be equal to 5 and 4.6 MW/cm^2 at 3 and 2 atm, respectively.

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