Appl. Phys. B 55, 54–59 (1992)

Applied Physics B Photophysics and Laser Chemistry

Influence of Cavity Configuration on the Pulse Energy of a High-Pressure Molecular Fluorine Laser

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Received 10 December 1991/Accepted 6 April 1992

Abstract. We report an investigation of a high-pressure molecular fluorine laser operating at 158 nm. Several cavity configurations were studied, including one employing a roof prism as the high reflector. A maximum VUV pulse energy of 237 mJ, corresponding to a specific output of 3.3 J/l was obtained when the laser was operated as a double-ended device. With single-ended operation the largest output energy was 176 mJ at a specific output of 2.5 J/l.

PACS: 42.55.Hq, 42.60.Da

The output pulse energy of discharge-excited molecular fluorine lasers has recently been increased to over 100 mJ compared to the 10 mJ per pulse typical of early devices. This improvement has followed experimental and theoretical work which suggested that the performance of the F_2 laser could be greatly enhanced by operating at high buffer gas pressures [1, 2].

The earliest report of operation of a discharge-excited F_2 laser at high buffer gas pressures was by Ishchenko et al. [1] who investigated an F_2 laser which could be operated at pressures of up to 10 bar. In that work a maximum output pulse energy of 15 mJ was achieved at a specific output energy of 1.0 J/l, and an efficiency of 0.17%. Yamada et al. [3, 4] investigated an F_2 laser which operated at a maximum buffer gas pressure of 8 bar. Their laser produced output pulse energies of up to 140 mJ, corresponding to a specific output of 1.7 J/l when excited with pump pulses of 12 MWcm^{-3}. The highest reported specific output pulse energy was reported by Kakehata et al. [5] who achieved an output of 2.9 J/l by employing a high peak excitation power density of 66 MWcm^{-3}. Voss and Nikolaus [6] have reported the operation of an F_2 laser at a high pulse repetition rate to yield high mean powers in the VUV. In their system discharge pumping at a specific pump power of 15 MWcm^{-3} with a pulse repetition rate of 50 Hz produced output pulse energies of 140 mJ, corresponding to a mean output power of 7 W.

In this paper we describe the investigation of an F_2 laser which operates at buffer gas pressures of up to 11 bar (absolute). We have studied the dependence of the output pulse energy on the parameters of the cavity employed. For the best of the cavities investigated, a total VUV pulse energy of 237 mJ was achieved, corresponding to a specific output of 3.3 J/l, which, to our knowledge, is the highest pulse energy and specific pulse energy reported to date for a discharge-excited F_2 laser.

1 Experimental Details

The F_2 laser used in this study was a discharge-excited laser employing a charge transfer circuit with automatic preionization [7], as illustrated schematically in Fig. 1. The laser vessel was constructed from stainless steel and was designed for a maximum working pressure of 11 bar. The internal electrode structure provides mountings for 50 ceramic capacitors each of 1 nF capacitance, placed in two rows along each side of the discharge gap. The preionization was provided by 200 inductively-ballasted pins positioned in two rows either side of, and parallel to, the discharge. The pins

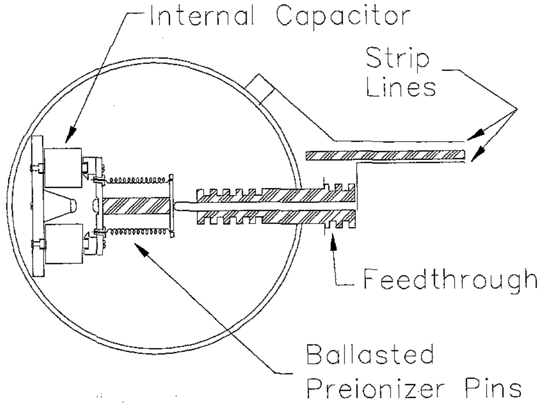

Fig. 1. Schematic diagram of the discharge structure of the high-pressure F_2 laser used in this work

were spaced at 10 mm intervals along the length of the discharge. The internal structure of the laser was designed to be as compact as possible in order to reduce the inductance of the inner discharge loop to a minimum, thereby allowing a rapid rise of the discharge current. The discharge gap was 14.5 mm and the length of the discharge was indicated by the arc pits on the two electrodes to be 990 mm. An examination of the dimensions of the F_2 laser beam indicated that the height of the discharge was 5 mm.

The single external capacitor of 150 nF capacitance could be charged to a maximum of 75 kV with the power supply available. Strip-lines connected the external capacitor to 7 feedthroughs which carried current to the internal capacitors via the preionization pins. The laser was switched with a spark-gap and was operated at a pulse repetition rate of one pulse every 4 seconds.

The internal mirrors forming the F_2 laser cavity were mounted on brass plates which were attached via a gimbal mounting to the end flanges of the laser vessel. For each mirror mount, the shafts of two micrometers passed through vacuum seals to contact the brass plates. Adjustment of the micrometers enabled the cavity mirrors to be rotated about two orthogonal axes, allowing the mirrors to be aligned normal to the length of the discharge. For all the cavities described in the present paper the F_2 laser cavity was aligned with the aid of a helium-neon laser beam defining the axis of the F_2 laser discharge. The cavity length was 1140 mm. The F_2 laser radiation emerged through a 6 mm thick MgF_2 window tilted at an angle of 10° to the axis of the laser so as to prevent reflections coupling back into the region of laser gain.

The pulse energy of the F_2 laser was measured with a pyroelectric energy meter (Gentec ED 200). To avoid attenuation of the VUV radiation due to the strong absorption on the Schumann-Runge bands of molecular oxygen present in the atmosphere, the energy meter was housed in a vacuum chamber connected directly to the end flange of the laser. Helium gas was flowed through the chamber containing the energy meter so as to continually flush away impurities from the beam path. The F_2 laser emits a small amount of collateral radiation with wavelengths in the 700–760 nm spectral range, due to weak laser transitions in atomic fluorine [8]. This radiation was also detected by the energy meter, but its contribution to the signal could be determined by allowing air into the beam path so as to completely absorb the VUV radiation. This procedure was performed for each of the cavities described in the present work, although the pulse energy of the visible laser radiation was always found to be small, typically 1–2 mJ.

The response of the energy meter is slightly wavelength dependent. Unfortunately the response of the energy meter at 158 nm is not known, and so following Yamada et al. we have used the spectral correction for radiation at 193 nm. Based upon the wavelength dependence of the spectral correction it is expected that by using the correction factor for 193 nm radiation we expect to *underestimate* the pulse energies of the F_2 laser at 158 nm.

Several configurations of the F_2 laser cavity were studied. For each of these the output laser pulse energy was optimized with respect to the partial pressure of fluorine, the pressure of helium buffer gas, and the external charging voltage. The results of these studies are described in the following sections.

2 Cavity A: Aluminized Rear Mirror and a Magnesium Fluoride Output Coupler

The first cavity investigated in the present work employed a rear mirror formed from a glass optical flat with the front surface coated in aluminium with a magnesium fluoride overcoat. The reflectivity of this rear mirror was approximately 85% at 158 nm. The output coupler was formed by a 3 mm thick uncoated magnesium fluoride flat. The two sides of the output coupler were not parallel, the wedge angle being approximately 5 mrad. Consequently a cavity was only formed between the rear mirror and one of the surfaces of the magnesium fluoride flat, and hence it is supposed that the reflectivity of the output coupler was simply that due to a single surface of magnesium fluoride. The refractive indices for ordinary and extraordinary rays in MgF_2 are $n_o = 1.465$ and $n_e = 1.479$ respectively [9], implying a single surface reflectivity of 3.6%.

With the cavity as described above the pulse energy was measured for gas mixtures consisting of a buffer gas pressure of 11 bar of helium and various partial pressures of fluorine in the range 6–12 mbar. A maximum VUV pulse laser energy of 105 mJ was recorded. However, during this study the F_2 laser pulse energy suddenly halved compared to that recorded previously for the same gas mixture. Upon examination of the rear mirror it was discovered that the aluminium and MgF_2 coating had been completely removed from a rectangular area of dimensions 14.5 mm by 5 mm. A replacement rear mirror was also damaged in the same way.

An important point to note is that after the rear mirror was severely damaged the F_2 laser continued to show laser oscillation and pulse energies of more than 50 mJ were recorded. Once the rear mirror had been damaged it would have provided a reflectivity of approximately 5% corresponding to that from a single surface of glass.

3 Cavity B: Multilayer Dielectric Rear Mirror and a Magnesium Fluoride Output Coupler

The rear mirror was replaced with a multilayer dielectric plane mirror of nominally 94% reflectivity at 158 nm, and an MgF_2 output coupler was employed as described above.

Figure 2 shows the measured VUV pulse energy as a function of the partial pressure of fluorine for various buffer gas pressures and for a charging voltage of the external capacitor of 75 kV. It is seen that for each buffer gas pressure there is an optimum pressure of fluorine, and that this optimum pressure increases steadily as the buffer gas pressure is raised.

The dependence of the pulse energy on the buffer gas pressure at a fixed partial pressure of fluorine of 15 mbar, for various charging voltages, is shown in Fig. 3. All the curves show the same general form: a rapid and approximately linear increase of the output pulse energy as the buffer gas pressure is raised, followed by a decline of the rate of increase in pulse energy with buffer gas pressure and even a decrease of the output for high buffer gas pressures and low charging voltages. The optimum buffer gas pressure in-

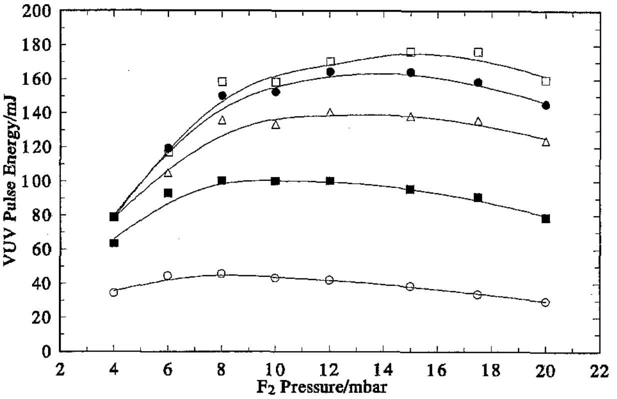

Fig. 2. The measured F_2 laser VUV pulse energy as a function of the partial pressure of fluorine for various buffer gas pressures. The charging voltage of the external capacitors was 75 kV, and the cavity was formed by a multilayer dielectric rear mirror of 94% reflectivity, and an MgF_2 output coupler. (○ 3 bar; ■ 5 bar; △ 7 bar; ● 9 bar; □ 11 bar)

creases as the charging voltage is raised which suggests that the observed decrease in the pulse energy for high buffer gas pressures and low charging voltages is caused by poor breakdown of the laser gas.

The maximum output VUV pulse energy measured for this cavity configuration was 176 mJ, for a fluorine pressure of 15 mbar, a buffer gas pressure of 11 bar and a charging voltage of 75 kV.

4 Cavity C: Magnesium Fluoride Rear Mirror and Output Coupler

For a cavity consisting of two uncoated MgF_2 optical flats, equal laser pulse energies would be expected to be emitted from the two ends of the F_2 laser. To avoid radiation being scattered from the rear end flange of the laser vessel and returning through the gain volume, the laser was operated with two identical tilted MgF_2 output windows so that laser radiation transmitted by the rear MgF_2 flat could emerge from the laser. This arrangement also allowed the F_2 laser pulse energy emerging from the rear of the laser to be measured.

The energy of the F_2 laser radiation which emerged from the front of the laser was measured for various combinations of fluorine pressure, buffer gas pressure and charging voltage as described above. The curves obtained were very similar to those shown in Figs. 2 and 3. The optimum gas mixture was found to be the same as for the cavity in which a dielectric rear mirror was employed.

The VUV pulse energy emitted from the rear of the F_2 laser was measured as a function of the buffer gas pressure with a fluorine pressure of 15 mbar and a charging voltage of 75 kV. The ratio of the pulse energy measured at the front of the laser to that recorded at the rear was found to have the same value (0.8), within the experimental errors, for all buffer gas pressures. The pulse energy emitted from the rear of the laser was slightly higher than that from the front due to the fact that the output window at the front of the laser was slightly damaged, since it had been used many

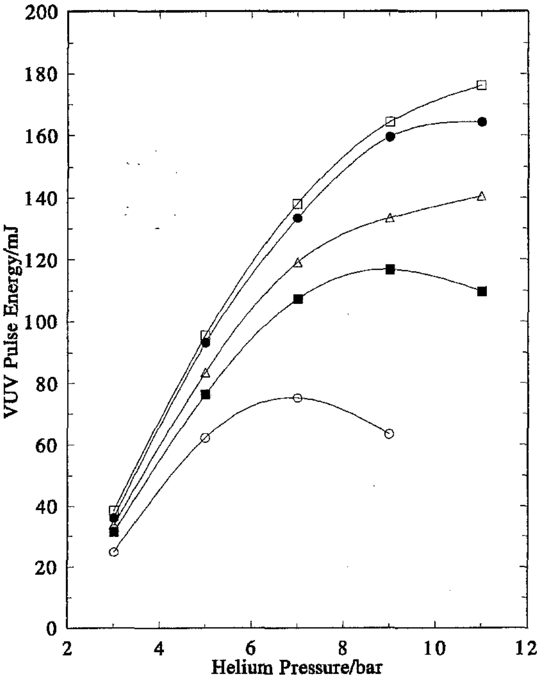

Fig. 3. The measured F_2 laser VUV pulse energy as a function of the buffer gas pressure for various charging voltages. The partial pressure of fluorine was 15 mbar, and the cavity was formed by a multilayer dielectric rear mirror of 94% reflectivity, and an MgF_2 output coupler. (○ 40 kV; ■ 50 kV; △ 60 kV; ● 70 kV; □ 75 kV)

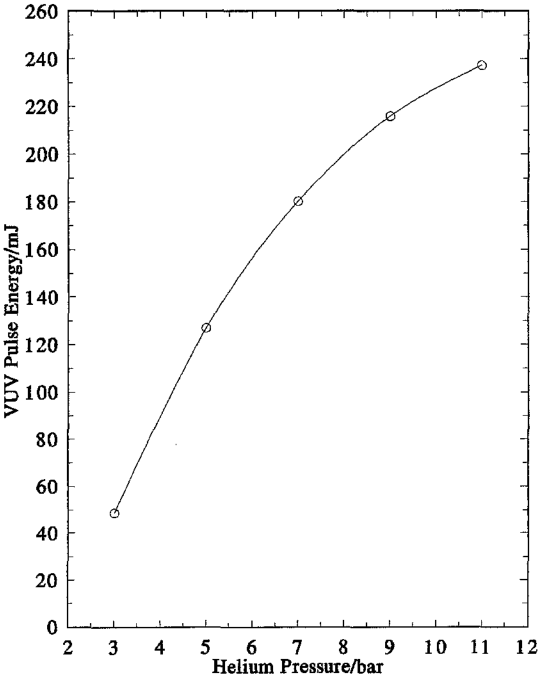

Fig. 4. The total VUV F_2 laser pulse energy as a function of the buffer gas pressure, measured from both ends of the laser when used with an MgF_2 output coupler and rear mirror. The charging voltage was 75 kV, and the partial pressure of fluorine was 15 mbar

times, whereas the rear output window had not been used previously.

Figure 4 shows the total VUV pulse energy emitted from both ends of the laser as a function of the buffer gas pressure for a fluorine pressure of 15 mbar and a charging voltage of 75 kV. The largest measured total VUV pulse energy emitted by the laser was 237 mJ.

5 Cavity D: A Magnesium Fluoride Roof Prism as a Rear Reflector and a Magnesium Fluoride Output Coupler

As an alternative to a dielectric rear mirror, an MgF_2 roof prism was employed as a rear reflector. The prism was 15 mm tall and 26 mm wide with a 90° apex angle which was accurate to 10 seconds of arc. The roof prism was held in a holder of similar design to that used for the rear mirrors described above, so that the angle of the normal of the front face of the prism could be rotated through two orthogonal planes. The cavity was aligned as follows. The beam from a helium-neon laser was adjusted so as to pass through the centre of the discharge at the front end of the laser and to strike the apex of the roof prism at the rear of the laser. The prism and the MgF_2 output coupler were then rotated so that the front face of the prism and the output coupler were normal to the beam from the helium-neon laser. It should be noted that the apex of the roof prism was approximately 1 mm below the centre of the discharge and the height of the roof prism could not be adjusted. As a consequence, the axis of the laser cavity formed was not quite parallel to the axis of the discharge, but since the angle between these axes was small the output pulse energy is not expected to have been greatly affected.

The output VUV pulse energy was measured for various combinations of fluorine pressure, buffer gas pressure and charging voltage. Similar results to those obtained for the cavities employed previously were obtained. A maximum VUV pulse energy of 155 mJ was measured for a fluorine pressure of 15 mbar, a bufffer gas pressure of 11 bar and a charging voltage of 75 kV.

6 Laser Without Cavity

The effect of mis-aligning the laser cavity on the laser pulse energy was investigated using the cavity consisting of the roof prism as a high reflector and an MgF_2 output coupler. The cavity could be deliberately mis-aligned without disturbing the laser vessel by adjusting the micrometers. The construction of the mirror mounting was such that the normals of the mirrors could be rotated through a maximum angle of 3° in two orthogonal planes. This angle was sufficient to ensure that radiation reflected by one of the mirrors could pass through no more than 100 mm of the 990 mm long gain region of the laser. Thus by mis-aligning one of the mirrors in this way no laser cavity was formed.

The F_2 laser pulse energy was measured for the optimum gas mixture of 15 mbar of fluorine and 11 bar of buffer gas and for a charging voltage of 75 kV whilst the output coupler was mis-aligned as described above and with the roof prism aligned as described in the previous section. With this arrangement the laser cavity therefore consisted of a high reflector at one end of the laser and, effectively, no output coupler. The laser pulse energy was found to be exactly the same as when the cavity was properly aligned.

The roof prism was then also mis-aligned as above whilst the output coupler was similarly mis-aligned. The properties of a roof prism are such that rotation of the prism about an axis parallel to the apex of the prism does not alter the angle at which radiation which is internally reflected is returned. However, rotation about an axis perpendicular to the apex of the prism does cause the internally reflected radiation to be returned at an angle to the incident radiation. The radiation reflected from the front surface of the prism will be returned at an angle to the incident radiation in the same way as for an ordinary mirror. Hence the mis-alignment of the roof-prism and the output coupler would have resulted in there being no laser cavity formed at all.

With this arrangement of the cavity optics the output pulse energy was measured for buffer gas pressures between 3 bar and 11 bar, for a fluorine pressure of 15 mbar and a charging voltage of 75 kV. For all buffer gas pressures in this range the output pulse energy was found to be, within experimental errors, half of that measured when a cavity formed from a roof prism and an MgF_2 output coupler was employed.

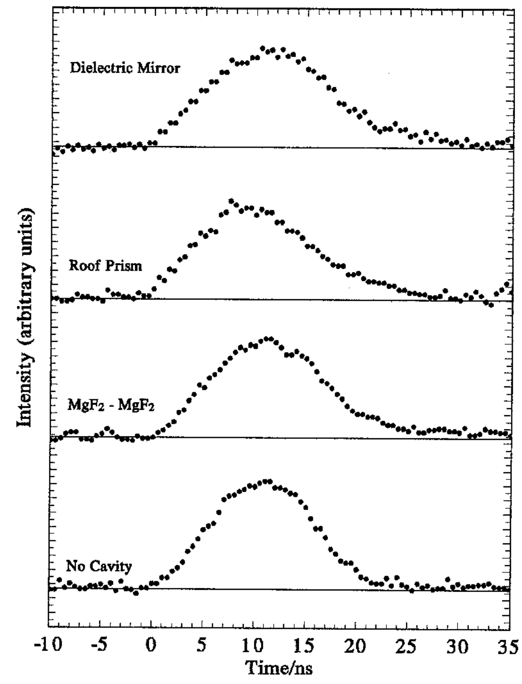

Fig. 5. The measured temporal profiles of the F_2 laser radiation for four of the laser cavities described. All the profiles were recorded for a gas mixture consisting of 15 mbar of fluorine and 11 bar of helium, and with a charging voltage of 75 kV. The pulses have been displaced vertically and their peak intensities normalized in order to allow comparison of the temporal profiles

7 Pulse Shapes for the Different Cavities

The temporal profiles of the F_2 laser pulses were measured by scattering the F_2 laser radiation with a 0.25 mm thick wire onto the cathode of a fast solar-blind vacuum photodiode (I.T.L. 1850 CsI), the output of which was recorded by a 2 gigasample/s digital oscilloscope (Hewlett Packard 54111D).

Figure 5 shows the pulses recorded for the different cavities described above including the case when no cavity was present. There is little variation in the shape of the output pulses, and all have a full width at half maximum of approximately 13 ns.

8 Discussion and Conclusion

We have studied various cavity configurations for a high-pressure molecular fluorine laser. In terms of the output pulse energy, the best of the cavities investigated in the present study was the cavity consisting of two MgF_2 optical flats. The maximum pulse energy achieved with this cavity was 237 mJ which corresponds to a specific output of 3.3 J/l. To our knowledge, this is both the highest pulse energy and the greatest specific output reported for a discharge-excited F_2 laser.

Of those cavities investigated which produced laser emission from only one end of the laser, the greatest pulse energies were achieved with a multilayer dielectric rear mirror and an MgF_2 output coupler. For this cavity the highest measured F_2 laser pulse energy was 176 mJ, corresponding to a specific output of 2.5 J/l.

The pulse energies obtained with a roof prism used as the rear reflector were approximately 10% lower than those obtained with a multilayer dielectric rear mirror. This reduction is probably a result of losses in the prism caused by the finite absorption by magnesium fluoride of radiation at 158 nm [10]. However, the use of a roof prism as a rear reflector does offer the advantage of a high damage threshold as well as being relatively inexpensive.

The disadvantage of the MgF_2–MgF_2 cavity is that the emission is from both ends of the laser. If, however, a high reflector is used as the rear mirror so as to produce laser emission from only one end of the laser, it is found that the output pulse energy is not as great as the total output achieved with the MgF_2–MgF_2 cavitiy. This decrease in pulse energy is probably due to the increased radiation flux within the gain volume during the laser pulse which increases the saturation of the gain of the laser transition. This hypothesis is supported by the results of the investigation of the output pulse energy for the case when no optical cavity was present. The fact that the pulse energy was found to be independent of whether or not an output coupler was employed, and that the pulse energy was exactly halved when no rear mirror was present suggests that for the F_2 laser described in this work the laser emission was very strongly saturated.

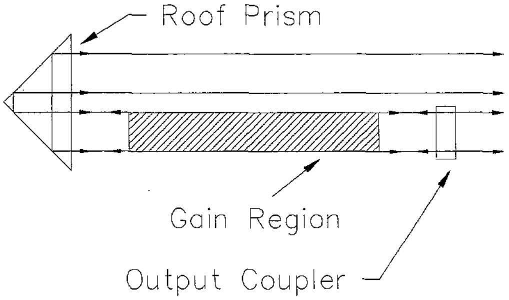

Fig. 6. A schematic diagram of the proposed cavity which is equivalent to the cavity formed from two MgF_2 flats, but which produces laser emission from only one end of the laser

Figure 6 shows a cavity which is equivalent to the cavity formed by two MgF_2 optical flats but which produces emission from only one end of the laser. The cavity is formed by an MgF_2 flat, which acts as an output coupler, and the surface reflection from the front face of a roof prism. For this cavity the apex of the roof prism is displaced from the axis of the gain region so that radiation transmitted into the body of the prism is reflected back parallel to the laser axis but is displaced so that it does not pass back through the gain region. This reflected radiation will emerge through the front window of the laser along with the laser radiation transmitted by the output coupler. This cavity has yet to be tested.

Our results suggests that the output pulse energy of the F_2 laser when used with a cavity formed from a highly reflecting rear mirror and an MgF_2 output coupler might be increased if the profiles of the electrodes were altered so as to increase the height of the laser discharge. The effect of this change would be to reduce the pump power density and the laser gain, and consequently prevent the strong saturation which we have observed, whilst increasing the volume from which the laser radiation could be extracted.

The data presented in Fig. 3 suggests that a molecular fluorine laser could be operated at buffer gas pressures higher than the safe working limit of 11 bar imposed by the construction of our laser vessel. In order to achieve a uniform glow discharge at pressures greater than 11 bar it would be necessary to increase the peak electric field appearing across the discharge gap, either by decreasing the size of the gap or by increasing the voltage applied to the gap. A molecular fluorine laser utilizing a Marx-bank arrangement as the source of charge to the internal capacitors would allow much larger voltages to be applied to the discharge gap whilst keeping the charging voltage of the external power system relatively low.

It should also be noted that the charge transfer circuit used in the present work has not been optimized. Yamada et al. [4] have demonstrated the importance of selecting correctly the values for the external and internal capacitances in order to achieve a rapid rise of the deposited power density into the discharge. In conclusion, the results of the present study indicate that by operating at buffer gas pressures greater than 11 bar, optimizing the laser cavity, as well as optimizing the excitation circuit of the laser, output pulse energies exceeding 0.25 J should be possible from a discharge-excited molecular fluorine laser.

Acknowledgements. The authors would like to thank the Electrical and Power Industries Sub-Committee of the Science and Engineering Research Council which funded this work through grant number

GR/F 99960. We would also like to thank Bernhard Ohnesorge for his help in constructing the high-pressure F_2 laser.

References

1. V.N. Ishchenko, S.A. Kochubei, A.M. Razhev: Sov. J. Quantum Electron. **16**, 707–709 (1986)
2. M. Ohwa, M. Obara: Appl. Phys. Lett. **51**, 958–960 (1987)
3. K. Yamada, K. Miyazaki, T. Hasama, T. Sato: Appl. Phys. Lett. **54**, 597–599 (1989)
4. K. Yamada, K. Miyazaki, T. Hasama, T. Sato, M. Kasamatsu, Y. Mitsuhashi: Paper UV 2.4 Technical Digest, Meeting of the IEEE LEOS, Orlanda, Florida, 15–20 October (1989)
5. M. Kakehata, E. Hashimoto, F. Kannari, M. Obara: Appl. Phys. Lett. **56**, 2599–2601 (1990)
6. F. Voss, B. Nikolaus: Lambda Science No. 3, Lambda Physik (1990)
7. A.J. Kearsley, A.J. Andrews, C.E. Webb: Opt. Comm. **31**, 181–184 (1979)
8. S. Sumida, M. Obara, T. Fujioka: J. Appl. Phys. **50**, 3884–3887 (1979)
9. P. Laporte, J.L. Subtil, M. Courbon, M. Bon: J. Opt. Soc. Am. **73**, 1062–1069 (1983)
10. M. Zukic, D.G. Torr, J.F. Spann, M.R. Torr: Appl. Opt. **29**, 4284–4292 (1990)