Scaling Demonstration of the XeF (C→A) Laser

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ABSTRACT

Operation of a scaled, injection-controlled XeF(C→A) laser is described. The output energy is 0.6 J per pulse from an extracted volume of 0.48 ℓ, which corresponds to an extraction energy density of 1.25 J/ℓ. The energy deposition in the gas is 105 J/ℓ and the intrinsic efficiency is therefore 1.2%. Also included is the first report of a repetitively-pulsed (1 Hz) electron-beam pumped XeF(C→A) laser.

1. INTRODUCTION

The XeF (C→A) excimer laser is an efficient, tunable source of blue-green radiation. A number of different pumping schemes have been used to drive this system including photolysis of XeF_2[1], transverse electric discharges[2] and long pulse[3] and short pulse[4] electron-beam pumping of high pressure gas mixtures. The highest single-pulse output energies, in excess of 40 J, have been produced using photolytic excitation, but the poor beam quality and the irreversible chemistry involved in these devices have limited their usefulness. Electric discharge excitation and long pulse electron-beam pumping produce low net gains (~1%/cm), which have so far prevented these lasers from being injection-controlled. The resulting output is spectrally very broad and the beam quality is limited to that obtainable from pulsed stable resonators. With short pulse electron-beams, however, the gain is high enough (2-3%/cm) for injection control to be used. The laser can then be tuned from 460 nm to 505 nm[5], and an extraction energy density as high as 1.6 J/ℓ with an intrinsic efficiency of 1.5%[4] has been achieved.

Previous short pulse experiments in this laboratory have used a Pulserad 110 machine, pumping extracted volumes of the order of 20 cm^3. Over a period of years a detailed understanding of the gas kinetics[6] and of the interaction between the gain medium and the optical cavity[7] has been developed, which has resulted in an optimized gas mixture and cavity configuration for the short gain-length device. The associated computer models have recently been used extensively in the design of the 480 cm^3 system to be reported here.

2. EXPERIMENTAL DETAILS

2.1 Electron-beam generator and laser cell

The experimental layout is shown in Fig.1. The electron-beam generator is a custom-built unit from Maxwell Laboratories Inc. (model no. 50168). The pulse length is 10 ns FWHM (measured in the laser cell) and the peak diode voltage and current are 550 kV and 83 kA respectively. The machine can be operated at repetition rates of up to 1 Hz. Diagnostics include a number of electrical monitors which are used to verify the machine performance on each and every shot. The electron-beam passes into the laser cell through a 25 μm titanium foil. The cell itself is made from 316 stainless steel and for these experiments is fitted with mounts for internal optics. These allow the laser mirrors to be positioned and adjusted within the laser gas, thus minimizing the unpumped length inside the cavity. The cell is sealed with uncoated fused-silica windows.

The laser gas components are introduced sequentially into the cell and are then mixed by circulation through an external flow loop. The mixture composition for the experiments reported here is 1.3 mbar of F_2, 10.5 mbar of NF_3, 10.5 mbar of Xe, 0.4 bar of Kr and 6.1 bar of Ar. The cell pressure is monitored using a pressure transducer (Data Instruments Inc., model no. AB200). Measurements of the pressure changes associated with the firing of the electron-beam can be analyzed to yield the energy deposition.

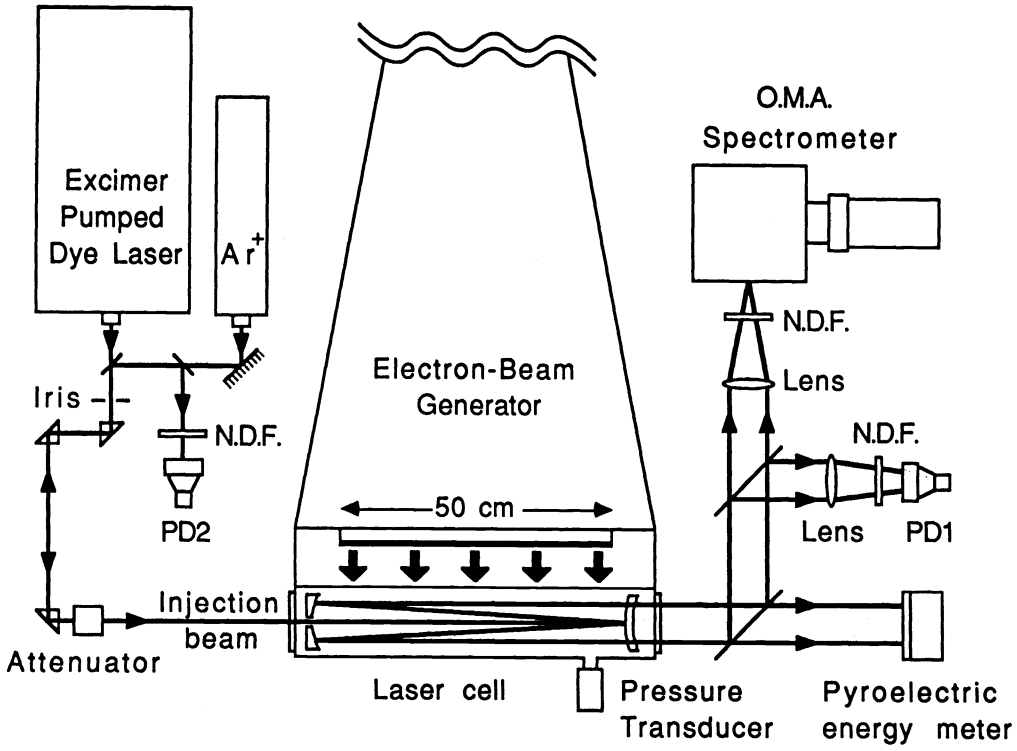

Figure 1. Schematic diagram of the experimental layout. N.D.F.: neutral density filters, PD1 and PD2 : vacuum photodiodes, O.M.A.: optical multichannel analyzer.

Spatial resolution of the deposition profile is obtained by exposing chlorostyrene film (Far West Technology, type 67-20) to the electron-beam. After 24 hours the film has darkened and its transmittance can be related to the local deposition value. The total energy deposited in the gas was thus determined to be approximately 112 J. The extracted laser volume is a cylinder 35 mm in diameter, defined by the cavity optics, and 500 mm in length, defined by the horizontal extent of the electron-beam. Its axis lies 25 mm from the foil. Within this 0.48 ℓ volume the deposited energy was 50 J, giving an average specific energy density of approximately 105 J/ℓ.

2.2 Injection laser and optical train

A commercial dye laser (Lambda Physik model no. FL3002) is used as the injection source. This is pumped by a long-pulse XeCl discharge laser (Lambda Physik LPX605i) with a resulting dye laser pulsewidth of 45 ns FWHM. With Coumarin 480 dye the laser can be tuned from 460 nm to 520 nm with a linewidth of less than 0.005 nm. An argon ion laser beam is combined with the dye laser output and is used for alignment and for wavelength calibration. The injection beam is attenuated to a pulse energy of 1 mJ before being introduced to the XeF (C→A) cavity.

The longer gain-length available from the larger electron-beam machine makes it possible to use higher magnification cavities than were practical with the Pulserad system. Increasing the magnification has a number of advantages, including a reduced far-field beam divergence, a reduced sensitivity to losses in the optical coatings and a greater tolerance of slight cavity misalignments. The magnification chosen here was 1.7, for which the cavity model predicted a laser output energy of 600 mJ. The mirrors are both coated onto silica substrates, the coatings having a high reflectivity (>99%) between 465 nm and 505 nm and a high transmittance (>85%) at the competing XeF (B→X) wavelengths near 350 nm. The back reflector is plano-concave with a radius of curvature of 2.73 m. The injected beam enters the cavity through a 1.5 mm diameter hole drilled through the center of this optic. The substrate for the output coupler is a meniscus lens with nominally infinite focal length. Its radii of curvature are ±1.61 m. The convex surface has a 21 mm diameter high-reflectivity spot deposited on it. The concave surface is anti-reflection coated. The mirror spacing is 56 cm.

2.3 Diagnostic and control subsystem

After leaving the laser cell the output beam strikes an uncoated silica beamsplitter which transmits 92% to a pyroelectric energy meter (Gentec Inc. ED500). The reflected 8% passes into an OMA/spectrometer combination (EG&G PARC model nos. 1229/1420/1461) and, via a second beamsplitter, into the vacuum photodiode PD1 (Hamamatsu Photonics R1193U-03). This is coupled to a transient digitizer (Tektronix 7912HB) and is used to monitor the temporal profile of the laser output. An identical photodiode, PD2, is illuminated by dye laser light which has passed twice through the XeF (C→A) cavity. Part of this beam has been amplified during the XeF gain pulse and this signal can therefore be used to confirm correct synchronization between the injection laser and the electron-beam machine. The spectrometer is fitted with a 300 lines/mm grating which allows broad spectral coverage, but which has a limited resolution of approximately 1 nm.

All of the diagnostic instruments are connected to a central PC AT-compatible microcomputer which is placed, with some of the instrumentation, in a Faraday cage. The remaining control electronics are housed in an RF-tight enclosure near the optical detectors. Experimental control and data acquisition are managed by a software package, specially developed in this laboratory, which arms the diagnostics, fires the lasers and collects the resulting data automatically. The hardware is accessed using a GPIB bus with a fiber-optic bus extender to eliminate electromagnetic interference outside the Faraday cage.

3. RESULTS AND DISCUSSION

3.1 Spectral behavior and output energy

Initial experiments have demonstrated good agreement between the predictions of the analytical model and the behavior of the experimental system. The effects of different optical configurations are summarized in Fig.2. In the absence of the cavity mirrors, but with the cell's silica windows aligned, the fluorescence spectrum is as shown in Fig.2(a). This is dominated by a strong superfluorescence peak at 249 nm, the wavelength of the KrF (B→X) transition, which clearly has enough gain for laser action using the windows as a cavity. However when the windows are misaligned the KrF peak intensity falls by a factor of three, confirming that the *single-pass* gain at this wavelength is not adequate to reach the saturation point. A second fluorescence peak is apparent in the region of 351-353 nm. This is due to the XeF (B→X) transition. By doubling the partial pressure of xenon it is possible to make this even stronger than the KrF laser visible in Fig.2(a). The broad XeF (C→A) peak near 480 nm is barely apparent in this figure, although it does become clearer when the abscissa is multiplied by ten. The sharp line at 498 nm is the KrF peak in second order and the blue wing of the broad underlying feature is due in part to emission from Kr_2F[8].

When the cavity mirrors are added, but no dye laser pulse is injected, the laser generates the well-known, free-running spectrum shown in Fig.2(b). The presence of the wavelength-selective optics is enough to suppress the two (B→X) lasers completely. The XeF (C→A) output energy under these circumstances is 90 mJ per pulse, corrected for the losses in the cell window and the first beamsplitter. The effects of the hole drilled in the back reflector make this cavity difficult to model in the free-running regime, but some free-running experiments were carried out using a 25 mm diameter stable resonator. The back reflector was then a high-reflectivity, 10 m radius concave mirror and the output coupler was a plane 70% reflector. The output energy predicted by the model was 120 mJ. The measured value was 125 mJ.

Fig.2(c) shows the output spectrum when the laser is injection controlled. The dye laser wavelength was set to 486.8 nm, which is near the peak of the XeF (C→A) gain curve. The measured linewidth is limited here by the resolution of the OMA system, and is probably much less than the apparent value of 1 nm. The model-predicted output energy is now 600 mJ which is in exact agreement with the measured value. The intrinsic efficiency is now 1.2% and the extraction energy density is 1.25 J/ℓ. Further increases in these numbers are expected when the injection intensity, the gas mixture and the optical configuration have been optimized.

3.2 Repetition rate performance

Scaling of this laser system to high average powers requires not only an increase in the single-pulse energy but also operation of the machine at significant repetition rates. There follows the first report of a repetitively pulsed electron-beam pumped XeF (C→A) laser. The laser performance is shown in Fig.3. The signals displayed there are from the pyroelectric energy monitor and from the cell pressure transducer. The laser was being operated at 1 Hz and the traces show the first ten shots of a sequence. The output on the first shot is approximately 480 mJ (this is less than the value measured above because the optics have been degraded by several weeks' operation in the corrosive laser gas mix). The second pulse is 125 mJ and the sequence then settles down to an average of 185 mJ per shot. The reason for the sudden fall-off in output is that the gas in the laser cell is unable to relax thermally between shots. The effect of the electron-beam is to heat the gas rapidly

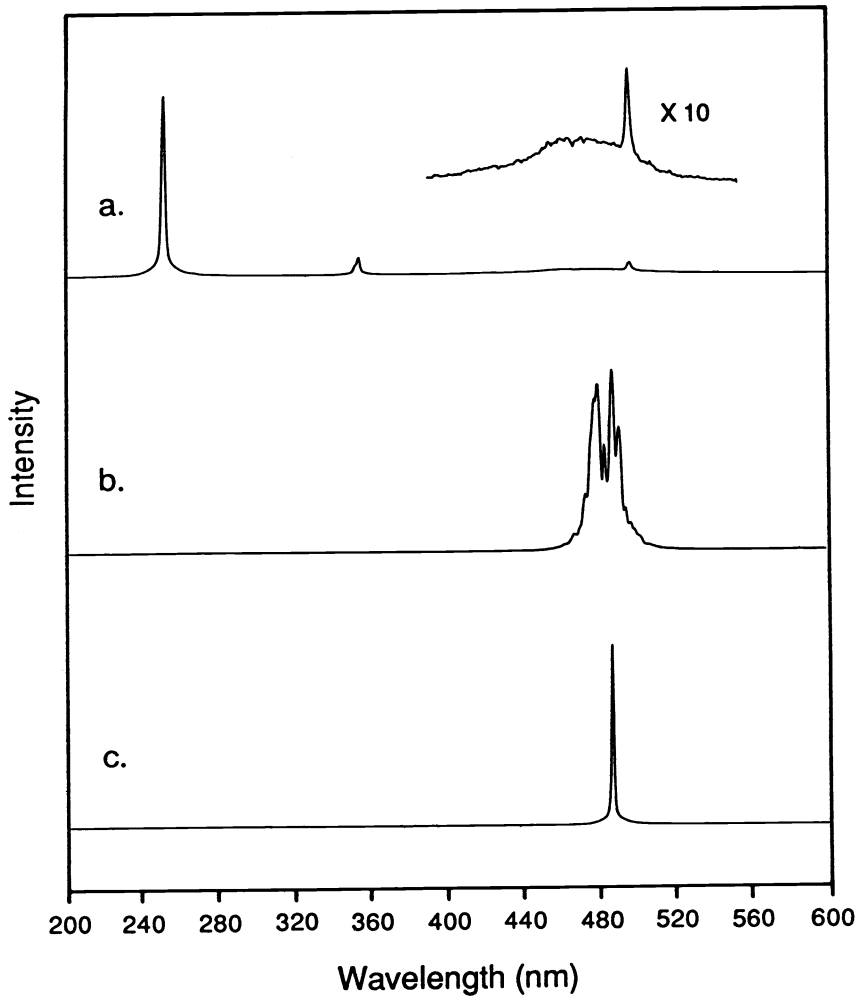

Figure 2. Spectral output of the laser with different optical configurations: (a) fluorescence with no mirrors but with cell windows aligned, (b) free-running laser spectrum with mirrors but with no injected beam, (c) injection-controlled laser output.

leading to thermal nonuniformities throughout its volume. Once pressure equilibrium has been reached (typically in a few tens of milliseconds) the remaining temperature variations are matched by corresponding density variations. The consequences of these are apparent if the argon ion alignment laser is left running when the electron-beam is fired. The transmitted beam is observed to be seriously disturbed by the swirling gas for 3-5 seconds after the electron-beam has been fired. The relaxation mechanism is a mixture of thermal conduction and the swirling convective processes observed above. Calculations of the conductive relaxation times for the lower thermal modes of the system confirm that one second is too short a period for relaxation to take place. Effective operation of a 1 Hz laser will therefore require the implementation of a flowing-gas cell.

It can be seen from the pressure transducer curve that there is no systematic reduction with time of the energy deposited per shot. The pressure jumps can be deduced by careful back-extrapolation through the acoustic noise which predominates at early times. (It is important not to rely simply on the late-time decay since the faster thermal modes will have relaxed completely by then and the energy associated with them will be missed out of the calculation.) The average measured pressure jump is 180 mbar which corresponds to a temperature jump of 8.3 k per shot. After the first few shots the increased thermal conduction balances the heat input at a mean temperature rise of about 16 K. The energy input per shot can be calculated if

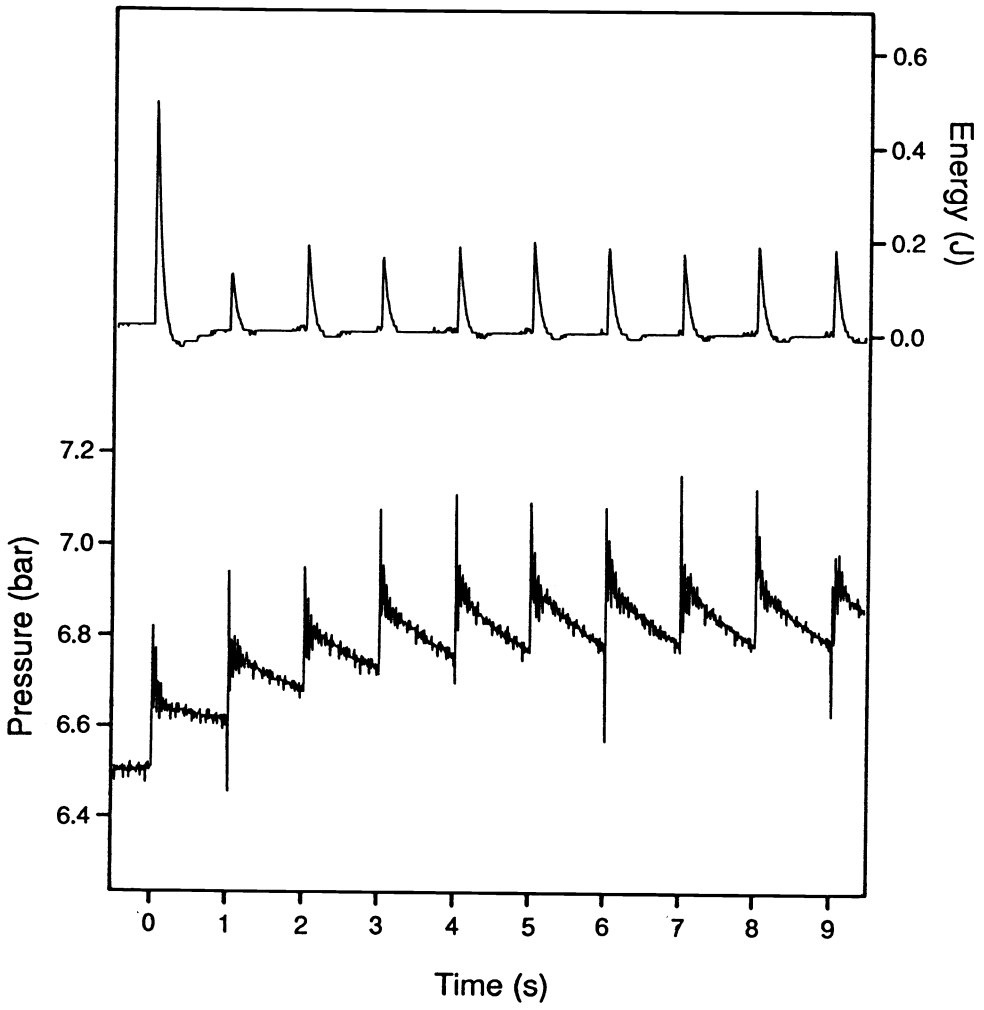

Figure 3. Output from pyroelectric energy meter and from laser-cell pressure transducer, showing energy per shot (equal to height of peak) and cell pressure over a sequence of 10 1 Hz shots.

the heat capacity of the gas is known. The volume of the system is 4.03 ℓ and it contains 6.5 bar of almost pure rare gases. The heat capacity is therefore approximately 13.6 J/K. The deposited energy is then approximately 113 J per shot which is in fortuitously good agreement with the value measured using chlorostyrene film. In fact the uncertainty on the pressure jump measurements is of the order of 10% because of the difficulty in assessing the pressure immediately after the electron-beam machine has fired.

4. CONCLUSIONS

It has been shown above that the XeF (C→A) laser can be scaled to volumes of the order of 1 ℓ using short pulse electron-beam excitation. The extraction energy density of 1.25 J/ℓ and the intrinsic efficiency of 1.2% are comparable with the best figures achieved using smaller systems. They are likely to be further improved by fine tuning of the experimental configuration. Despite the increased gain length it is still possible to suppress the competing (B→X) lasers by using wavelength-selective optics and by choosing an appropriately tailored gas mix. The analytical model of the system, developed for the earlier electron-beam machine, has proved to be very effective at predicting the properties of the scaled device. The high gains available in this system have allowed successful injection control of the laser and have made straightforward the use of relatively high magnification (M=1.7) optics.

5. ACKNOWLEDGEMENTS

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