Repetitively Pulsed Operation of an Injection-Controlled High-Power XeF($C \rightarrow A$) Excimer Laser

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***Abstract*—The operation at a 1 Hz repetition frequency for an injection-controlled electron-beam pumped XeF($C \rightarrow A$) excimer laser system is reported. A compact, halogen compatible closed flow loop incorporating a transverse in-line fan was used for gas circulation. An improved output-laser energy of 1.2 J per pulse with an intrinsic efficiency of 1.1% was achieved with a large aperture unstable resonator.**

I. Introduction

An efficient, high-power laser with broad-band wavelength tunability, and spectral bandwidth control in the visible region is of importance for various applications including optical communications and remote sensing. In recent years, the XeF($C \rightarrow A$) laser has been actively developed because of its very broad spectral bandwidth of ~ 50 nm full-width half-maximum (FWHM) centered at 490 nm. Thus, the XeF($C \rightarrow A$) laser is a scalable optical source that is continuously tunable over a large portion of the visible spectrum. Various types of excitation have been investigated [1]-[4] and efficient operation of this system has been achieved by means of electron-beam pumping. For a high excitation rate (~ 10 MW/cm^3) using a short-pulse electron beam, the gain of this excimer system exceeds 0.03 cm^{-1} near the peak of the tuning spectrum, which permits efficient injection-controlled operation with good beam quality by using an unstable resonator [2].

More recently, scaling experiments with an intense short-pulse electron beam have been performed in this laboratory in which the active volume was increased from ~ 0.02 to ~ 0.5 L [5]. Using a multicomponent high-pressure gas mixture comprised of F_2, NF_3, Xe, Kr, and Ar [6], [7], a specific laser energy output density of 1.7 J/L with an intrinsic efficiency of 1.3% were achieved at 486.8 nm, corresponding to an output energy of 0.8 J. Furthermore, the short-pulse electron-beam excited XeF($C \rightarrow A$) excimer laser was demonstrated to be continuously tunable between 450 and 530 nm with an output linewidth as narrow as 0.001 nm [8]. As previously reported in [5] and [9], the pulse repetition rate of this XeF($C \rightarrow A$) excimer laser system was limited to 0.1 Hz by transient gas turbulence effects since the gas flow rate in the laser chamber was insufficient to exchange the pumped gas volume between *e*-beam pump pulses. This letter reports improved laser performance of 1.2 J/pulse and, in particular, repetitive operation of up to 1 Hz using a compact, gas-flow (~ 5.7 m/s) system incorporating a transverse in-line fan. The flow medium characteristics of the flow loop was evaluated by means of an interferometric technique using an excimer-pumped pulsed dye laser as an illuminator.

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II. Experimental Setup

The electron-beam generator, described in detail elsewhere [5], [6], [10], produces a 650 keV, 90 kA pulse in 10 ns (FWHM) with a current density of 250 A/cm^2. It is capable of repetitive operation at up to 1 Hz. The 25 μm titanium anode foil was coated with a 5 μm layer of ion vapor deposited aluminum to prevent its interaction with the reactive fluorine in the laser gas mixtures.

A cross-sectional schematic of the flow system is depicted in Fig. 1. The laser cell was made of stainless steel 316 and the other flow parts were fabricated from aluminum alloy with Viton vacuum seals. The cross-sectional inner dimensions of the laser cell were 5 cm in width and 6.5 cm in height. The gas was circulated by a 10 cm diameter $\times$ 52 cm length transverse flow fan magnetically coupled to an external induction motor, which could be operated at pressures of up to 6.5 bar. The dimensions of the flow loop design were, to a large extent, constrained by the electron-beam diode and the magnetic coil geometries, since both of these could not be changed without considerable difficulty. The resulting 90 degree bend in the flow channel could form turbulent eddies which would interrupt the exchange of gas and degrade the flow uniformity inside the laser cell even at moderate gas-flow velocity. To avoid this, four concentric guide vanes whose representative radii were approximately 1.8, 2.4, 3.2, and 4.4 cm, respectively, were installed in each bend to minimize turbulence effects inside the laser chamber. Moreover, this bending contour also provided a gradual expansion and contraction of the flowing gas, since the flow loop must be expanded from 2.2 cm in the flow channel to 5.0 cm in the laser chamber. The outside total dimensions of the closed flow loop were 20, 40, and 70 cm, in height, width, and length, respectively. The effective overall gas volume of this setup was approximately 24 L which is a ~ 6 times larger volume than that used in the previous laser cell described in [5] and [6].

A cross-sectional contour of the deposition energy at 6.5 bar Ar, measured by means of a chlorostyrene film dosimetry, is shown in Fig. 2. To take full advantage of the pumped electron-beam volume, a square resonator geometry with an aperture dimension of 4.6 cm $\times$ 4.6 cm was designed for maximum laser output energy extraction. The averaged spatial energy for the cross section of the resonator volume was measured to be ~ 110

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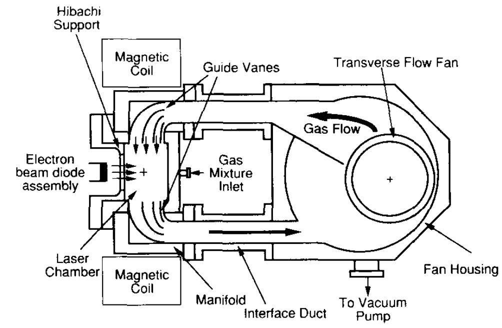

Fig. 1. Cross-sectional schematic of the closed flow loop incorporating a transverse in-line fan. The dimensions of the flow loop are 20, 40, and 70 cm, in height, width, and length, respectively. The overall gas volume is 24 L.

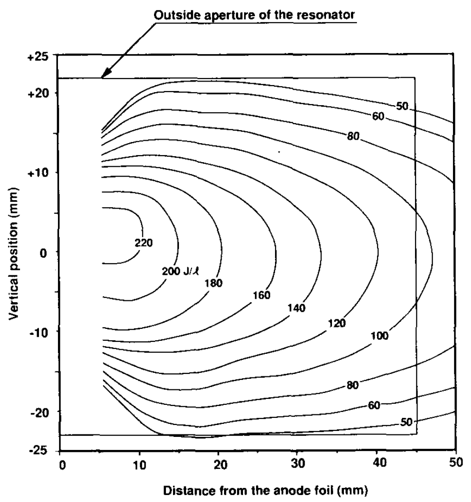

Fig. 2. Energy deposition profile in the laser chamber experimentally measured by using chlorostyrene film dosimetry. The spatially-averaged energy density was measured to be ~ 110 J/L for the entire 1 L optical resonator volume.

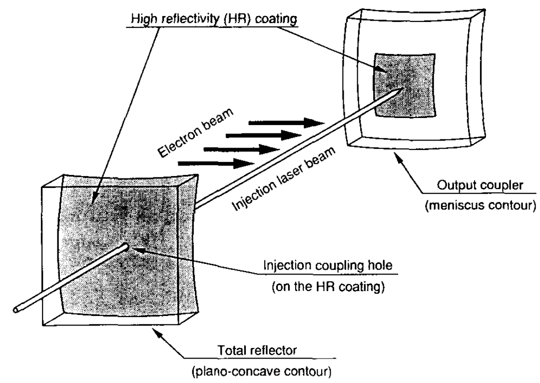

Fig. 3. A schematic drawing of the square unstable-resonator optics with an outside aperture dimension of 4.6 cm × 4.6 cm. These optics had fluorine protective coatings on the surface and were mounted directly on the ends of the laser cell acting as pressure windows.

J/L. The optical cavity configuration selected for this experiment was a positive-branch confocal unstable resonator as illustrated in Fig. 3. A resonator magnification of 1.67 was chosen for optimized performance in a mixture consisting of 1.3 mbar F_2, 16 mbar NF_3, 16 mbar Xe, and 1 bar Kr and completed to a total pressure of 6.5 bar with Ar as the buffer [6]. The concave total reflector (radius of curvature $R_1 = 3.0$ m) had a reflective coating ($R > 99.9\%$) and an AR coating between 465 and 505 nm deposited on the concave and the flat surface, respectively. An injection seed laser beam entered the resonator through a 1.5 mm diameter hole in the high-reflectivity coating located at the center of this reflector on the concave surface. The output reflector consisted of a meniscus lens with radii of curvature $-R_2$ and $R_2 = 1.8$ m and a 2.8 cm × 2.8 cm square reflective coating centered on the convex surface as shown in Fig. 3. The spacing between mirrors ($L = 60$ cm) was adjusted to the confocal position [$L = (R_1 - R_2)/2$]. These mirrors also had aluminum oxide fluorine protective coatings and were mounted directly on the ends of the laser cell in contact with the laser gas. As an injection-seed laser beam, a dye laser pumped by a XeCl excimer laser provided a 40 ns (FWHM) pulse. The seed beam diameter was adjusted with a telescope to achieve uniform injection and the typical peak injection intensity coupled through the hole corresponded to ~ 3 MW/cm^2.

The output energy was monitored by a pyroelectric detector and the temporal pulse duration, typically 10 ns in FWHM, was detected by a fast vacuum photodiode. The wavelength spectrum was measured by an OMA spectrometer. In order to characterize the initial flow characteristics in the absence of electron-beam pumping, the gas-flow velocity was probed by using small, 2 mm outer-diameter pitot tubes. The differential pressure was detected using a capacitance differential manometer at 6.5 bar Ar. Two pitot tubes were installed inside the flow channel just before the laser chamber. One tube was at the center, the other was located near the edge (5.0 cm from the wall) of the flow channel. The time history of flow recovery in the resonator active volume after an electron-beam pump pulse was recorded with a Michelson interferometer. The interferometer was illuminated by the excimer-pumped dye laser (40 ns, FWHM) tuned to 490 nm. Interferograms were taken at various times during and after electron-beam pump pulse deposition into a gas mixture consisting of 1 bar Kr and 5.5 bar Ar by adjusting the trigger delay between the electron-beam generator and the dye laser. The temporal jitter between the probe pulse and the electron-beam firing was less than 10 ns. The sensitivity of the interferometer (per fringe shift) corresponded to a gas-density variation ($d\rho/\rho$) of 5×10^{-4} for 6.5 bar Ar [11]. The imaging system used to record the interferometric pattern consisted of a two-dimensional charge-coupled device (CCD) array with 240 × 240 pixels in a 5.5 × 6.5 mm distribution with a saturation light level of 1 μJ/cm^2 at the visible wavelengths. The interferometer output was sampled using an uncoated quartz beam splitter and the image was focused onto the CCD array using a 50 cm focal length lens.

III. Results

The gas-flow velocity in the channel was measured to be 5.7 m/s at the center and 5.2 m/s near the edge in 6.5 bar Ar, showing a reasonably uniform velocity distribution across the flow channel. This flow velocity corresponded to the exchange of approximately 35 laser cell fills between electron-beam shots at 1 Hz. Interferometric measurements indicated that the gas-

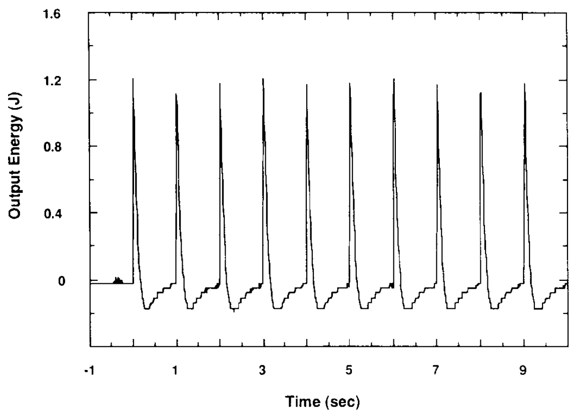

Fig. 4. Output signal from a pyroelectric energy monitor. The heights of the peaks corresponds to the energy per pulse. The trace depicts 10 individual laser shots obtained in a 1 Hz sequence. The wavelength and spectral width are 486.8 and 0.005 nm, respectively.

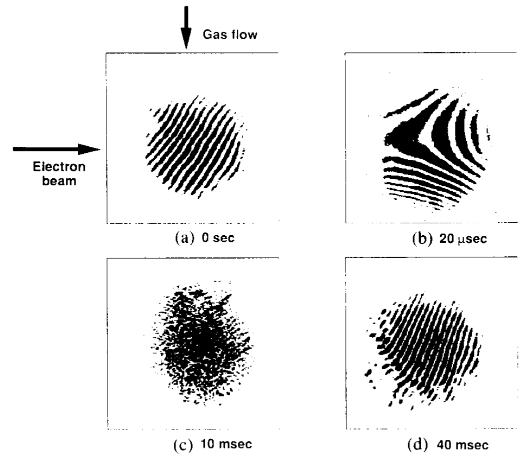

Fig. 5. Interferograms obtained with a two-dimensional CCD array before and after an electron-beam pump pulse. (a) Initial flow condition, (b) 20 μs, (c) 10 ms, and (d) 40 ms after an electron-beam pumping pulse.

density variation ($d\rho/\rho$) in the active region of the laser chamber was less than the interferometer sensitivity in 6.5 bar Ar, demonstrating excellent flow uniformity despite the 90 degree bend in the flow loop.

In single-laser shot operation, the timing between an electron beam and the injection dye laser was carefully adjusted to obtain an optimum laser pulse energy stability. A maximum energy per pulse of 1.2 J was extracted at an injection wavelength of 486.8 nm using the square unstable resonator geometry. Repetitive laser performance was demonstrated in Fig. 4 which depicts the signal from a pyroelectric energy monitor for 10 shots in a 1 Hz sequence. The output energy remained at 1.2 J/pulse throughout this 1 Hz series, the same output level observed under a single-shot operation, without shot-to-shot energy degradation due to thermal turbulence. Thus, both the high laser energy output and repetitively pulsed operation were demonstrated for a scaled electron-beam pumped XeF($C \rightarrow A$) laser amplifier system.

Interferograms were taken during and after an electron-beam pump pulse to determine the minimum optical cavity recovery time of this device. Typical images of interferograms are shown in Fig. 5, where (a) shows the initial condition before the electron-beam pulse. At 20 μs, the medium distortion was clearly observable and was found to start from close to the anode foil where the highest energy is deposited into the gas mixture as shown in Fig. 5(b). Fig. 5(c) illustrates the maximum perturbation, occurring 10 ms after the electron-beam pump pulse, as the acoustic wave travels across the laser volume. Finally, at 40 ms after the electron-beam pulse, the flow uniformity was almost restored as shown in Fig. 5(d). Therefore, it is believed that the present compact closed flow loop could achieve stable laser output energy performance at repetition rates of up to 25 Hz.

In conclusion, the scaling of the XeF($C \rightarrow A$) laser system has been demonstrated not only for high-laser output energy per pulse but also for repetitively pulsed operation with a compact flow system. Reliable performance of a 1 Hz electron-beam pumped XeF($C \rightarrow A$) laser with an output energy of 1.2 J per pulse and an intrinsic efficiency of 1.1% at 486.8 nm was achieved with a magnification 1.67 square unstable resonator geometry.

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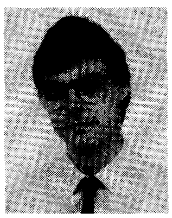

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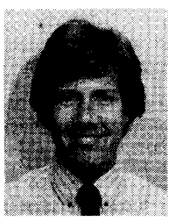

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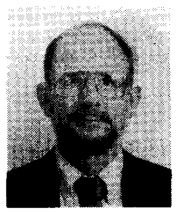
Roland Sauerbrey (M'85), for a photograph and biography, see p. 100 of the January 1991 issue of this JOURNAL.



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Frank K. Tittel (SM'72–F'86), for a photograph and biography, see p. 100 of the January 1991 issue of this JOURNAL.