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Photoinitiated F_2+H_2/D_2 chain-reaction laser with high electrical efficiency*

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Performance characteristics are reported for a pulsed HF/DF laser initiated by photodissociation of F_2. Laser energy of 292 J is obtained from a 12.8-l active volume for 2.5% HF content at 1-atm total pressure, giving 8.1% chemical efficiency and 29% electrical efficiency. Thirty-three percent electrical efficiency is obtained with a 109-J laser energy. DF lasing produces 144 J with 14% electrical efficiency. Far-field measurements show a uniform beam profile with angular half-angle divergence of 5.5 mrad, in good agreement with the value expected for multimode operation of the large-Fresnel-number stable resonator used.

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I. INTRODUCTION

A variety of methods have been used for initiation of reaction in pulsed HF chemical lasers. For H_2-F_2 chain-reaction lasers, initiation is normally achieved by dissociation of F_2 and has been accomplished by electric pin discharge,[1] electric discharge with uv preionization,[2] electric discharge with electron-beam preionization,[3] direct e-beam dissociation,[4] and uv photodissociation.[5–8] Continuing interest has been shown in extending several of these schemes to larger devices. Measurements of laser energy and far-field beam properties are reported here for a 10 – 16-l device which produces larger output energies and higher electrical and chemical efficiencies than photoinitiated chemical laser reported previously. Deuterium (^{2}H) is distinguished from hydrogen (^{1}H) in Sec. III, but not in Sec. II.

II. EXPERIMENTAL METHOD

Figure 1 is a schematic of the photoinitiated HF/DF laser, which is generally characterized by (i) a gas-mixing apparatus and procedure designed to minimize H_2-F_2 prereaction, (ii) an average transverse path for uv flashtube radiation of about 9 cm, and (iii) isolation of optical cavity components by an inert buffer gas. The apparatus is similar to a DF-CO_2 laser described by Parker and Hess,[9] although no HF or DF lasing was reported for that device.

The H_2-F_2—diluent mixture is stabilized against prereaction by the addition of oxygen. Contact time between H_2 and F_2 is minimized by mixing in the gas-supply manifold. The mixing/filling procedure typically requires 30—60 sec. For typical mixtures using N_2 as diluent an increase of the time delay before ignition from 30 sec to 2 min reduces the laser output energy by less than 10%. Fluorine is acquired and stored as a 10% mixture. Additional diluent and oxygen are introduced and allowed to mix completely with fluroine before hydrogen is added. The hydrogen is then completely mixed before the gas enters the reactor. Mixture flow rate and composition are remotely controlled by the valves and flowmeters indicated in Fig. 1; the cryogenic mixing provision shown was not used for the data reported here.

The laser assembly shown in Fig. 1 is constructed from a thick-walled 6061 Al alloy tube with 14-cm inside diameter. It is divided by gate valves into a central reactor section 1.5 m long, and shorter end cells which serve to isolate the cavity optical components from the reacting gases. The internal U-shaped flashlamps illuminate a volume of reagent mixture approximately 128 cm long. From two to eight lamps were used for measurements reported here; the active volume of the laser is reduced as more lamps are installed due to a smaller clear aperture. Each of the 60-cm flashtubes is powered by a separate 0.815-μF capacitor, and all tubes are simultaneously discharged by grounding a common bus through a single spark-gap switch. In addition to variation of the number of tubes and the electrical energy dissipated in each tube, measurements were made for two different wall conditions: bare 6061 Al (low uv reflectivity) and a Teflon-covered wall (high uv reflectivity). The stable resonator consisted of a 40-m-radius Au-coated mirror and a planar output coupler with 235-cm separation.

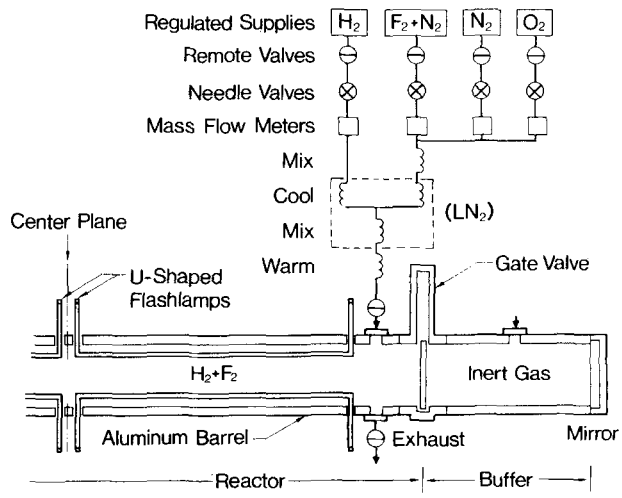

FIG. 1. Diagram of the photoinitiated HF/DF laser, illustrated for HF lasing and N_2 diluent. Half of the symmetric mechanical assembly is shown; the other end includes the optical output coupler.

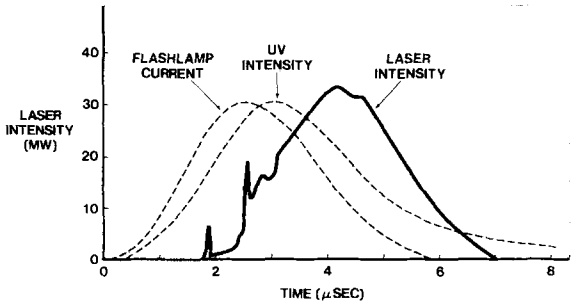

FIG. 2. Time relationships between (i) the current profile for a 30-kV discharge through a flashtube, (ii) the associated uv time profile measured at 288 nm, and (iii) the resulting HF laser output pulse. The laser was operated with 8 flashtubes and 1 atm of 1.25% H_2, 7.5% F_2, 0.5% O_2, and 90.75% N_2, with room-temperature gas mixing.

The run procedure is of some consequence since pre-reaction or premature ignition has caused difficulties in several $H_2 + F_2$ lasers.[10,11] After evacuation of the device, the gates are closed and both the buffer cells and the reactor are filled. A sequenced timing circuit then opens the gates, fires the flashtubes, and immediately evacuates the laser to minimize exposure of the quartz flashtubes to HF. The laser is operated in a closed hood room; other separated areas are used for gas mixing, laser control, and target interaction experiments.

III. RESULTS AND DISCUSSION

Figure 2 relates the temporal profiles of the flashtube current, the flashtube uv output, and the resulting laser emission pulse. The current trace is for a 30-kV discharge. The uv profile was measured with a silicon photodiode, utilizing a 288-nm transmission filter with FWHM of 23 nm to sample the flashtube spectral distribution near the 285-nm peak of the fluorine absorption spectrum. The laser output pulse was monitored by a Ge(Au) detector, which sampled the entire cross section of the beam by means of a CaF_2 wedge beam splitter, a collecting mirror, and a reflective diffuser. The 87-J laser pulse of Fig. 2 has FWHM of 2.6 μsec. A second beam from the splitter (or the primary beam for the initial work) was directed to a thermopile calorimeter (Scientech model 364) for beam-energy measurement. the splitter sampling fraction was measured directly using two calorimeters.

A. Water-vapor attenuation and spectral content

The HF laser energy transmitted over a fixed enclosed air path of 5.7 m was measure for two values of water-vapor content (9.5- and 1.0-Torr partial pressure, determined by the dew point) to permit air-absorption corrections to measured laser energies. An intensity ratio of 0.823 was measured for this partial-pressure difference of 8.5 Torr, which corresponds to 43% relative humidity at 22 °C. Corrections for ambient water-vapor partial pressures different from 8.5 Torr were made by a simple exponential extension of this measurement. No air-absorption corrections were made for DF. In a separate study of the laser spectral composition,[12] a holographic technique was used to measure the time-integrated spectrum for a four-flashtube configuration. Most of the HF beam energy is associated with several P-branch transitions in the first three vibrational bands and corresponds to wavelengths in the 2.7—3.0-μ region.

B. Far-field beam profile

The far-field characteristics of the laser beam are of particular interest because the device is used for laser beam-target interaction measurements. With a 165-cm-focal-length mirror, burn patterns were observed as a function of mirror-to-target distance. The resulting spot sizes showed a well-defined minimum at the mirror focal plane. The energy profile in that plane was measured by scanning across the diameter of the beam in both the vertical and the horizontal directions with a calorimeter apertured to 0.25-cm diameter. The results are shown in Fig. 3. Most of the energy falls within a central area which is about 1.7 cm in diameter (FWHM) and is quite uniform in energy density. Some asymmetry is expected from the aberration incurred in focussing the beam off-axis in the horizontal plane.

C. Divergence

For the data of Fig. 3, the eight flashtubes in the reactor limited the clear aperture of the laser to about 10 cm in diameter. The far-field divergence expected from a stable resonator of large Fresnel number in high-order multi-mode operation has been approximated by Fortin,[13] under the assumption of equipartition of

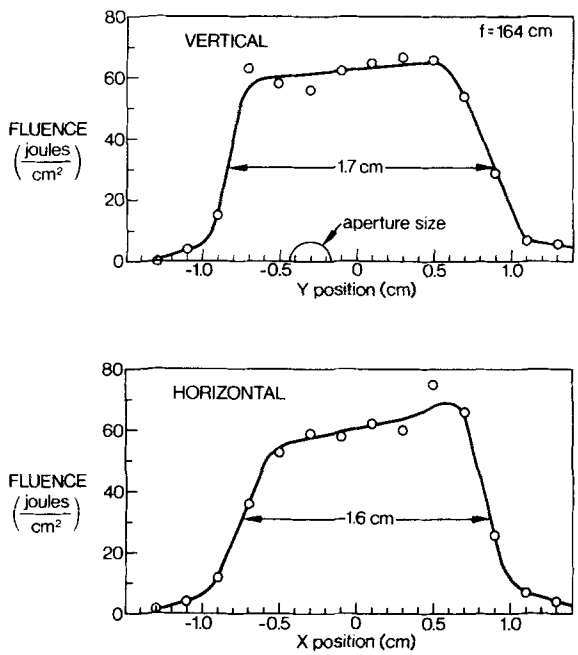

FIG. 3. Far-field HF laser beam profiles measured in the focal plane of an $f = 165$ cm mirror with an apertured calorimeter. A CaF_2 beam splitter and a second calorimeter provided energy normalization. Asymmetry is partly due to focussing the beam off-axis in the horizontal plane. The laser conditions were the same as for Fig. 2.

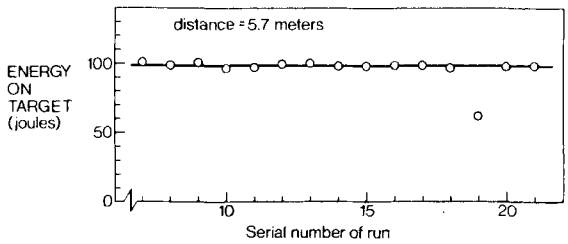

FIG. 4. Absolute magnitude of laser energy on a target 5.7 m from the laser, for several sequential shots with the laser conditions of Fig. 2.

energy between transverse modes. With the waist diameter $w = 10$ cm, cavity length $l = 235$ cm, and mirror radius $R = 40$ m, the predicted full angle divergence to the 30% intensity point $\theta = 1.06\, w(lR)^{-1/2} = 10.9$ mrad. The measured 30% intensity spot diameter of 1.8 cm (Fig. 3) and the mirror focal length give a measured divergence of 1.8 cm/165 cm = 10.9 mrad.

D. Repeatability

Oxygen or cryogenic mixers are commonly used in H_2-F_2 lasers to suppress prereaction which can result in poor shot-to-shot repeatability. The 15 sequential laser shots used for the vertical beam-profile scan of Fig. 3 were also monitored for absolute laser energy output. These absolute energies are plotted in Fig. 4. All but one of these points lie within a band of ± 2% from their average.

E. Parameter variation

Table I shows examples of the effect of varying several of the laser conditions. The right-hand column of this table shows the laser output energy as a function of five selected parameters: gas-mixture molar percentages of H_2, F_2, and O_2; capacitor charging voltage, which determines the level of fluorine photodissociation; and output mirror coupling. With fluorine fixed at 5%, variation of hydrogen from 1.25 to 2.5% has no measurable effect at these conditons. Model calculations (not reported here) indicate that this behavior is associated with conditions in which lasing terminates early in the reaction pulse. The fluorine variation shows that for these conditions increasing the fluorine-to-hydrogen molar ratio F_2/H_2 from 4 to 6 doubles the output, but the next change from 6 to 8 in F_2/H_2 gives no improvement. Optimum operation with fluorine-rich mixtures has been reported for a number of $H_2 + F_2$ lasers; optimization of the molar ratio F_2/H_2 has given, for example, $F_2/H_2 = 2$ (Ref. 14), $F_2/H_2 = 3$ (Ref. 6), and $F_2/H_2 = 4$ (Ref. 1), for various device configurations and initiation methods. It is to be noted, however, that the photoinitiated laser reported in Ref. 5 produced maximum output energies at F_2/H_2 ratios of unity and less under conditions for high specific energy operation (80 J/l-atm). The variation of oxygen in Table I gives a well-defined optimum at 0.5%; for these conditions 0.25% oxygen allows prereaction to become a limiting factor, whereas 0.75% oxygen suppresses the pumping reactions as well as prereaction. Degradation of laser output with excess O_2 has been observed with this laser for many different operating conditions. The change shown in charging voltage is reflected in laser performance, but the output energy does not increase in direct proportion to capacitor energy for the conditions shown. Finally, laser performance shows only a weak dependence on output mirror coupling, for transmission between 54 and 87%.

TABLE I. Variation of laser energy output as a function of laser conditions. Nitrogen, not shown among the gas molar percentages, makes up the remainder of each gas mixture. These data are for room-temperature gas mixing, 1-atm total pressure, and for initiation by four flashtubes with 6061 Al reactor wall.

Variable	%H_2	%F_2	%O_2	Capacitor voltage (kV)	Mirror coupling (%out)	E(laser) (J)
H_2	1.25	5.0	0.5	30	87	61
	1.9					63
	2.5					61
F_2	1.25	5.0	0.5	30	87	52
		7.5				110
		10.0				109
O_2	1.25	7.5	0.25	30	87	75
			0.5			104
			0.75			82
Voltage	1.25	7.5	0.5	30	87	104
				36		130
Coupling	1.25	7.5	0.5	30	87[a]	107
					75[b]	98
					54[c]	98

[a] Uncoated sapphire.
[b] Coated sapphire.
[c] Silicon.

TABLE II. Variation of laser energy out as a function of energy stored in the flashtube capacitor bank for 6061 Al wall. Nitrogen diluent comprises the remainder of each gas mixture. These data are for ambient temperature gas mixing and 1-atm total pressure. The two couplers are bare sapphire (87%) and coated sapphire (75%).

Molar % of $H_2/F_2/O_2$	Output mirror transmission	Number of flashtubes	E_{in} (kJ)	E(laser) (J)	η_e (%)	η_c (%)
2.5/5.0/0.25	87%	2	0.73	51	7.0	0.6
			1.06	71	6.7	0.8
		4	1.47	91	6.2	1.3
			2.11	122	5.8	1.7
1.25/7.5/0.5	75%	8	2.04	95	4.7	3.4
			2.93	132	4.5	4.7
			3.55	141	4.0	5.0
			4.22	152	3.6	5.4

F. Variation of flashlamp energy

Table II shows the variation of laser energy out as a function of input flashtube energy for the case of the 6061 Al reactor wall. The effective laser volume was approximately 16 l for the two-lamp data, 12.8 l for the four-lamp data, and 10 l for the eight-lamp measurements. This volume reduction largely accounts

TABLE III. Selected performance characteristics of the photoinitiated pulsed chemical laser with the Teflon-covered wall. The molar fraction of H_2 or D_2 is 1.2% and the mixing temperature is ambient. The two output couplers are sapphire and silicon.

Index No.	Lasant	Diluent	p (total) (atm)	O_2 (%)	F_2 (%)	No. of lamps	Mirror coupling (% Out)	E (laser) (J)	FWHM (μsec)	η_e (%)	η_c (%)
1	HF	N_2	1.0	0.25	10	2	87	148	2.9	14	3.3
2	HF	Ar	1.0	0.6	10	2	54	149	3.5	29	3.3
3	HF	Ar	1.0	0.6	10	2	54	109	5.0	33	2.4
4	HF	Ar	0.6	0.5	7.4	2	54	72	13.8	21	2.7
5	DF	Ar	1.0	0.6	10	4	87	144	3.8	14	4.0
6	HF	Ar	1.0	0.7	10	4	87	292	2.7	29	8.1

for the drop from 122 to 95 J out for similar input energy into four and then eight lamps; the volumes involved are also important in comparing the first and last electrical efficiencies tabulated in Table II. The chemical efficiencies η_c listed are based on the volumes cited and are governed by the hydrogen content for these mixtures. The electrical efficiencies η_e are total electrical efficiencies defined as 100 $E(\text{laser})/E_{in}$ where E_{in} is the total electrical energy stored in the flashlamp capacitor bank.

G. Selected performance points

Table III shows several operating conditions which are of special interest because of the associated laser performance. The underlined entries are emphasized in the following discussion. The range of performance shown in Table III is associated with three extensions of operating conditions not reflected in Tables I and II: (i) a uv-reflective Teflon liner was added to the reactor wall; (ii) a second diluent, argon, was incorporated and, (iii) initial gas pressure was included among the variable parameters.

The first line of Table III for N_2 diluent shows about the same laser energy from two lamps as the maximum obtained with eight lamps in Table II. Several conditions are the same for line 1 of Table III and the second line of Table II: effective reactor volume (using 2 lamps), flashlamp energy (1.06 kJ), diluent (N_2), total pressure (1 atm), and output coupling (87%). The improvement in electrical efficiency from 6.7 to 14% is due to the higher uv reflectivity of the Teflon wall lining, combined with a gas mixture containing a larger fluorine component.

Line 2 of Table III shows another factor-of-2 improvement in electrical efficiency as a result of changing from nitrogen to argon as diluent. In terms of laser operation, equal laser energy was obtained from a 36-kV flashlamp discharge in line 1 and a 25-kV discharge in line 2. Among the factors involved in this improvement is the temperature dependence of the kinetic rates (HF-HF self-deactivation rates in particular) coupled with the higher temperatures resulting from the use of a monatomic diluent. The use of argon, however, requires the higher molar fraction of oxygen shown, in order to inhibit preignition; output energy is quite sensitive to this oxygen fraction.

The third line of Table III shows an optimized electrical efficiency of 33% with over 100-J laser energy.

In a series of measurements which explored ways to control laser pulse length the total initial gas pressure was varied from 0.2 to 1.0 atm using nitrogen diluent, and 0.6 to 1.0 atm using argon. Line 4 of Table III shows conditions for a 72-J pulse which has been "stretched" to 14 μsec FWHM by reducing the total pressure, the F_2 fraction, and the electrical energy input. Pulses of similar FWHM obtained with reduced pressures and nitrogen diluent were lower in energy by a factor of 4.

Line 5 gives one set of conditions for DF lasing. As expected from energy-transfer considerations, use of nitrogen as DF diluent gave poor results for all conditions tested.

A combination of four flashlamps and the Teflon uv reflector produced 292 J as shown in line 6, with 29% electrical efficiency and 8.1% chemical efficiency.

The results of Table III may be compared to the maximum output conditions for two other recently reported photoinitiated HF lasers. Batovskii and Gur'ev[6] obtained 37 J from a 4.5-l device using fluorine-rich (55%) mixtures at 250 Torr total pressure, giving $\eta_c = 0.64\%$ and $\eta_e = 3.9\%$. Chen *et al.*[5] used 1.1 atm total pressure (10% F_2) in a 0.1-l device to obtain 8 J energy out, with $\eta_c = 4\%$ and $\eta_e = 1.3\%$. In both of these studies, the flashtube geometry was coaxial with the laser volume, with the flashtube either on the centerline,[6] or forming a concentric shell around the laser volume.[5] Considering photoinitiated chemical lasers more broadly, Parker and Hess in 1973 reported 189 J of 10.6-μ radiation from a 10-l DF-CO_2 device, and 12% electrical efficiency.[9] Among photoinitiated pulsed chemical lasers, then, the results of Table III represent (*i*) the largest absolute energies reported for both HF and DF wavelengths and (ii) the highest electrical and chemical efficiencies attained. It may be noted that we have used partial pressures of H_2 and F_2 which are lower than the maximum values used for other photoinitiated devices,[5] and much lower than those of e-beam initiated lasers.[4,15,16]

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[1]J.S. Whittier and R.L. Kerber, IEEE J. Quantum Electron. **QE-10**, 844 (1974).
[2]J.V. Parker and R.R. Stephens, Appl. Phys. Lett. **22**, 450 (1973).
[3]R. Hofland, M.L. Lundquist, A. Ching, and J.S. Whittier, J. Appl. Phys. **45**, 2207 (1974).

[4]R.A. Gerber, E.L. Patterson, L.S. Blair, and N.R. Greiner, Appl. Phys. Lett. **25**, 281 (1974).
[5]H.L. Chen, R.L. Taylor, J. Wilson, P. Lewis, and W. Fyfe, J. Chem. Phys. **61**, 306 (1974).
[6]O.M. Batovskii and V.I. Gur'ev, Sov. J. Quantum Electron. **4**, 801 (1974).
[7]G.G. Dolgov-Savel'ev, V.F. Zharov, Y.S. Neganov, and G.M. Chumak, Sov. Phys.-JETP **34**, 34 (1972).
[8]D.B. Nichols, K.H. Wrolstad, and J.D. McClure, J. Appl. Phys. **45**, 5360 (1974).
[9]J.V. Parker and L.D. Hess, *IEEE International Electron Devices Meeting, Washington*, 1973 (IEEE, New York, 1973).
[10]N.R. Greiner, IEEE J. Quantum Electron. **9**, 1123 (1973).
[11]R.W. Getzinger, Los Alamos Scientific Laboratory Report No. LA-5659, 1974 (unpublished).
[12]C.R. Pond, R.B. Hall, and D.B. Nichols, Appl. Opt. (to be published).
[13]R. Fortin, A.K. LaFlamme, and F. Rheault, Can. J. Phys. **50**, 583 (1972).
[14]R. Hofland, A. Ching, M.L. Lundquist, and J.S. Whittier, SAMSO Report No. TR-74-195, 1974 (unpublished).
[15]N.R. Greiner, L.S. Blair, and P.F. Bird, IEEE J. Quantum Electron. **QE-10**, 646 (1974).
[16]R. Aprahamian, J.H.S. Wang, J.A. Betts, and R.W. Barth, Appl. Phys. Lett. **24**, 239 (1974).