a cubic chirp of $1.6 \text{ kHz}/\mu\text{s}^3$ which for a pulse length of $2.5 \mu\text{s}$ and an output energy of 1 J corresponds to a modulation coefficient per unit output power of $4 \times 10^{-3} \text{ Hz/W}/\mu\text{s}^3$. These figures indicate a scaling of chirp with spot size roughly as σ^{-5} , in good agreement with previous experimental work [3], and at slight variance with theory—presumably due to the major approximation in the treatment of the mode.

IV. DISCUSSION

The results presented here do not only extend the spectral measurements on pulsed CO_2 lasers to higher levels of energy and greater beam diameters than previously, they also confirm that the laser-induced theory applies to these domains. In particular we have proven that it is possible to construct high-energy long pulse frequency stable CO_2 laser oscillators suitable for the types of application described in the introduction. The only problem encountered in the device was optical damage to intracavity components; obviously those in the contracted beam experience the highest intensities and are thus most susceptible to damage. The intensity at the plane total reflector is twice as high as at the negative lens [5] and as expected this total reflector was the first component to exhibit damage. The ZnSe Brewster window adjacent to it also showed pitting. The Brewster windows may easily be avoided by joining the CW gain tube to the total reflector and negative lens with bellows, or alternatively by omitting the CW section and utilizing a different mode selection technique such as injection mode selection or the use of an intracavity etalon in the expanded beam. Damage to the total reflector could doubtless

be ameliorated by assembly in clean conditions (not available in this study) and by further reducing the pulsed intracavity intensity by decreasing the reflectivity of the output coupler. Better suppression of the gain-switched spike in the laser output should also be effective in this regard, but requires an intracavity intensity of about $5 \text{ W} \cdot \text{cm}^{-2}$ before pulsing the TEA section. The large beam diameter in the pulsed module which is vital in obtaining freedom from the laser-induced chirp also results in the large mode volume necessary for high-energy operation. Clearly the output energy scales roughly as σ^2 , so the use of magnifications even greater than four could prove useful from the output energy viewpoint.

REFERENCES

- [1] R. M. Huffaker, "Global wind measuring satellite system (WIND-SAT) feasibility studies," in *Proc. 2nd Topic. Meet. Coherent Laser Radar*, Aspen, CO, Aug. 1983.
- [2] D. V. Willetts and M. R. Harris, "An investigation into the origin of frequency sweeping in a hybrid TEA CO_2 laser," *J. Phys. D*, vol. 15, pp. 51-67, 1982.
- [3] —, "Scaling laws for the intrapulse frequency stability of an injection mode selected TEA CO_2 laser," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 810-814, May 1983.
- [4] —, "Laser-induced frequency sweeping in an electron-beam sustained carbon dioxide laser," *Opt. Commun.*, vol. 49, no. 2, pp. 151-154, 1984.
- [5] D. C. Hanna, C. G. Sawyers, and M. A. Yuratich, "Telescopic resonators for large-volume TEM₀₀-mode operation," *Opt. Quantum Electron.*, vol. 13, no. 6, pp. 433-508, 1981.
- [6] A. Crocker, H. Foster, H. M. Lamberton, and J. H. Holliday, "Pulsed atmospheric-pressure carbon dioxide laser initiated by a cold-cathode glow-discharge electron gun," *Electron. Lett.*, vol. 8, no. 18, pp. 460-461, 1972.

A Miniature High-Power KrF Laser Excited with a Capacitively Coupled Discharge

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Abstract—A KrF excimer laser excited in a capacitively coupled discharge device made out of commercial BaTiO_3 doorknob capacitors is described. The discharge volume of 1.4 cm^3 is formed by a 3 mm bore into four capacitors glued together in a line. A maximal laser output energy of 1.7 mJ (1.2 J/l) in a 5.0 ns long pulse was achieved.

CAPACITIVELY coupled (CC) discharge devices of the transverse discharge type, incorporating dielectric electrodes, have successfully been used to achieve lasing in CO_2 [1], [2], HF [3], N_2 [4], and Ne [5]. Besides the approach of Newman [6], who realized a XeF and KrF-laser using a

longitudinal CC-discharge, to our knowledge no successful attempts have yet been performed to apply this excitation technique to the class of excimer lasers.

In most CC-discharge devices, flat or profiled BaTiO_3 slabs are used as electrodes. However, the dielectric electrodes can be formed more easily by simply drilling a cylindrical hole into a block of a suitable dielectric material [7]. In such a device the circular segments of the bore surface, adjacent to the outer metallic electrodes, serve as discharge electrodes. Besides mechanical simplicity, this configuration has the advantage of providing a uniform electric field inside the discharge volume, which favorably affects the homogeneity of the discharge.

In our letter we report the performance of a KrF-excimer laser excited with a modified version of the CC-discharge device

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Fig. 1. (a) Cross-sectional illustration of the laser device. (b) Laser circuit with storage capacitor. (c) Laser circuit without storage capacitor.

described in [7]. Discharges in typical He-Kr-F₂ mixtures at pressures ranging from 0.6 to 2.8 bar yielded laser action in KrF at a wavelength of 248 nm with pulse durations ranging from 5.0 to 7.5 ns (FWHM) and output energies up to 1.7 mJ. This laser pulse energy obtained without sophisticated optimizations is considerably larger than that achieved with rare gas halide lasers excited in other unconventional discharge systems [6], [8].

An outline of the laser device is shown in Fig. 1(a). Four 3.6 nF doorknob capacitors which have been bored through their diameters are epoxied together in a line using 10 mm long pyrex glass tubes as connectors between each other. The capacitors are carefully aligned so that the bores, having a diameter of 3 mm and a length of 50 mm, share the same axis. The discharge channel thus formed has a total length of 200 mm and a volume of 1.4 cm³. It is ended with quartz Brewster windows equipped with gas inlets. The laser gases were prepared in a gas handling system and fed into the laser through flexible tubes. For all measurements the laser was evacuated and refilled with a fresh portion of the actual gas mixture. Lasing is achieved with a 300 mm long resonator consisting of a dielectric total reflector and partial reflectors having a transmission of 20, 50, and 92 percent, respectively.

The charge of a 25 nF capacitor loaded to 25 or 30 kV was transferred to the four laser "capacitors" via a spark gap [Fig. 1(b)]. From the resonance frequency of the electric circuit which was measured to be 10 MHz, we derive a rise time of the voltage across the laser in the order of 50 ns. Neglecting losses in the circuit, the peak voltage across the laser was calculated to be maximally 32.5 and 39 kV, respectively, due to its smaller capacity of about 14 nF compared to the storage capacitor.

The laser pulse was monitored by an EG & G FND 100 Q photodiode in combination with a 0.3 m monochromator. The pulse energy was measured with a Gen Tec ED-100 pyroelectric energy meter. The laser output energy achieved with He-Kr-F₂-mixtures containing 0.5 percent F₂ and 5 percent

Fig. 2. Laser output energy obtained with a He-Kr-F₂ mixture containing 0.5 percent F₂ and 5 percent Kr as a function of total fill pressure and initial charge voltage.

Kr as a function of total pressure and load voltage is shown in Fig. 2. The output energy increases with pressures in the range from 0.6 to around 2 and 2.8 bar for an initial load voltage of 25 and 30 kV, respectively. Above these pressures only weak or no laser action at all can be observed, probably due to discharge instabilities. At a voltage of 25 kV the maximum output of 1.3 mJ could also be obtained with He-Kr-F₂ mixtures containing 2 and 10 percent Kr. The highest fill pressure at which laser action could be produced was then 2.2 and 1.8 bar, respectively. From this we can derive that the benefit of a higher pump rate of KrF* due to the presence of more Kr is compensated by the adverse effect of a high Kr partial pressure on the discharge homogeneity.

With a load voltage of 30 kV the maximum energy was measured to be 1.7 mJ. Moreover, the pressure regime in which laser action can be observed is extended to 2.8 bar. This result indicates that the broad pressure regime in which our device produces homogeneous discharges without preionization can still be extended by increasing the rate of the voltage change across the electrodes.

The fluorine concentration was varied between 0.25 and 2 percent, showing little effect on the laser performance. We have to assume that these measurements concerning the fluorine partial pressure are not necessarily typical, as the fluorine concentration is probably subject to substantial changes due to chemical reactions in the tubings and the laser device itself. The degradation of the laser gas was observed to be very fast indeed. Moreover, the reproducibility of the laser output was only in the order of 20 percent. These problems, however, should be overcome by selecting more suitable materials for the parts which are in contact with fluorine, and by establishing a gas flow in the discharge channel. A further improvement can certainly be expected if a fused dielectric material rather than a sinter is used.

The results in Fig. 2 were obtained with a resonator consisting of a dielectric total reflector and an uncoated quartz flat. Experiments with resonators having a higher internal reflectivity produced more reproducible results at somewhat lower output energies.

In the case of a charge voltage of 25 kV, the laser pulse duration shortens from 7.5 to 5.5 ns as the total fill pressure is

increased from 0.6 to 2.0 bar. In the experiments run at a voltage of 30 kV, the pulse duration was 5 ns independent of fill pressure ranging from 1.0 to 2.8 bar. The maximum peak power of the laser thus amounts to about 340 kW, which is a specific power of 240 kW/cm³. The achieved specific output energy of 1.2 J/l is comparable with the one obtained in conventional transverse discharge systems. These attractive laser specifications are contrasted by the rather poor overall efficiency of $1.5 \cdot 10^{-4}$ obtained with our setup. The most prominent energy waste in our experimental arrangement arises from the disproportion of the initially stored energy to that which can be deposited into the laser gas (see [1] and [7]) in a single charging and discharging cycle of the laser device. Thus, considerable improvements should be attainable by optimizing the geometry of the discharge device, thereby avoiding excess stray capacities, and by careful design of the external pulse-forming circuit.

A promising simplification of the laser setup is obtained when the laser "capacitor" is charged directly to 30 kV and then short circuited with a spark gap, as shown in Fig. 1(c). Additional capacitors can then be avoided. As the total circuit capacity in this case is higher than in the configuration shown in Fig. 1(b), the change of the voltage across the laser is slower unless the inductivity of the circuit is decreased accordingly. A slower rise of the voltage across the discharge electrodes, however, will affect the homogeneity of the discharge negatively. Realizing the circuit shown in Fig. 1(c) by short-circuiting the storage capacitor of 25 nF in the circuit used above [Fig. 1(b)], we measured a resonance frequency of 4 MHz. With this configuration, laser action in KrF could be achieved. But the highest output energy obtained at a charge voltage of 30 kV and at a fill pressure of 1.8 bar was only 370 μ J. Moreover, no laser could be observed at pressures above 2.0 bar. In

conclusion, we have shown that the KrF laser can be excited in a technically very simple CC-discharge device. Without any preionization, homogeneous discharges were observed in a He-Kr-F₂ mixture containing 0.5 percent F₂ and 5 percent Kr up to a total pressure of 2.8 bar. Laser pulses with an energy of 1.7 mJ at a specific energy of 1.2 J/l could be generated.

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REFERENCES

- [1] C. P. Christensen, "Pulsed transverse electrodeless discharge excitation of a CO₂ laser," *Appl. Phys. Lett.*, vol. 34, pp. 211-213, 1979.
- [2] H. Hokazono, K. Midorikawa, M. Obara, and T. Fujioka, "High-power, long-pulse CO₂ laser transversely excited by a damped oscillating discharge through dielectric electrodes," *Rev. Sci. Instrum.*, vol. 54, pp. 719-721, 1983.
- [3] D. B. Cohn and P. M. Lee, "HF laser excited by a capacitively coupled discharge," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 1743-1745, Dec. 1983.
- [4] V. Hasson, H. M. von Bergmann, and E. G. Jones, "Ultraminiature high-power gas discharge lasers excited through high dielectric constant ceramic material," *Rev. Sci. Instrum.*, vol. 51, pp. 384-385, 1980.
- [5] D. Schmieder, D. J. Brink, T. I. Salamon, and E. G. Jones, "A high pressure 585.3 nm neon hydrogen laser," *Opt. Commun.*, vol. 36, pp. 223-226, 1981.
- [6] L. A. Newman, "XeF* and KrF* waveguide lasers excited by a capacitively coupled discharge," *Appl. Phys. Lett.*, vol. 33, pp. 501-503, 1978.
- [7] H. M. J. Bastiaens, T. Gerber, and P. J. M. Peters, "A compact capacitively coupled N₂ laser with a new electrode design," *Opt. Lett.*, vol. 9, pp. 113-115, 1984.
- [8] D. Cleschinsky, D. Damasch, H. J. Eichler, and J. Hamisch, "XeF-laser with longitudinal discharge excitation," *Opt. Commun.*, vol. 39, pp. 79-82, 1981.

Efficient Generation of Picosecond Coherent Tunable Radiation Between 190 and 212 nm by Sum-Frequency Mixing from Raman and Optical Parametric Radiations

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Abstract—An efficient sum-frequency mixing of optical parametric radiation and stimulated Raman radiation has been used to generate picosecond continuously tunable coherent radiation ranging from 190 to 212 nm with energies of 20–40 μ J. An ordinary KDP crystal was phase-matched by using a combination of long and short wavelength incident waves.

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PRACTICAL techniques for generating coherent tunable UV radiation around 200 nm using nonlinear crystalline media [1]–[7], particularly in the picosecond time domain, have not yet become well established. Such light sources are needed for fast transient photoemission and photoelectron spectroscopies in photochemistry and solid-state physics. The simplest way of obtaining coherent tunable UV radiation is by second harmonic generation (SHG) from a tunable visible