Photopumping of a C III Ultraviolet Laser by Mn VI Line Radiation

Niansheng Qi[(a)] and Mahadevan Krishnan[(b)]
Section of Applied Physics, Yale University, New Haven, Connecticut 06520
(Received 27 April 1987)

Multiple-pass gain is reported at 2177 and 2163 Å in C III ions in a vacuum-arc discharge, pumped by Mn VI line radiation from a laser-produced Mn plasma. These Be-like uv lasers pumped by resonant photoexcitation are prototypes for soft-x-ray lasers in higher-Z, isoelectronic analogs.

PACS numbers: 42.55.Hq

This Letter presents evidence for lasing at 2163 and 2177 Å in C III ions in a vacuum-arc discharge. The population inversion in C III is pumped by 310-Å line radiation from Mn VI ions in a laser-produced Mn plasma. The Mn plasma is created adjacent to the vacuum-arc discharge. The Mn VI pump line radiation is resonant with the $2s^2\,{}^1S$–$2s4p\,{}^1P^\circ$ transition in C III, and selectively pumps the $2s4p$ level. Figure 1 shows the concept. Collisions in the C III discharge rapidly transfer the pumped quanta to other levels in the $n=4$ shell. Population inversions are then produced between these $n=4$ levels and the $n=3$ lower levels. A detailed atomic model,[1] supported by measurements, has shown that the $4p$-$3d$ line at 2177 Å and the $4f$-$3d$ line at 2163 Å offer the highest gains in such a scheme. For conditions typical of these experiments, enhanced fluorescence of a factor ≈ 150 times the spontaneous emission levels were predicted,[1] at both these wavelengths. Single-pass, gain-length products of ≈ 0.4 were predicted.[1] Enhanced fluorescence of ≈ 180 times the spontaneous emission levels were measured at both wavelengths.[1] The peak, single-pass, gain-length product measured at both these wavelengths was ≈ 0.5, as described below. A 1-m-long Fabry-Perot resonator was constructed, in an attempt to drive the gain medium into saturated laser oscillation. Because of the strong time dependence of the gain, this resonator allowed only ≈ 50 passes. With the high cavity losses, the net gain-length product after 50 passes was ≈ 4.5, which was insufficient to drive the laser medium into saturated oscillation. The stimulated amplification obtained with the resonator is consistent with an amplification of only a factor of ≈ 100 above the fluorescent levels in the cavity. Nevertheless, these results constitute the first observation of inversions and gain at uv wavelengths with resonant photoexcitation as the pump mechanism.

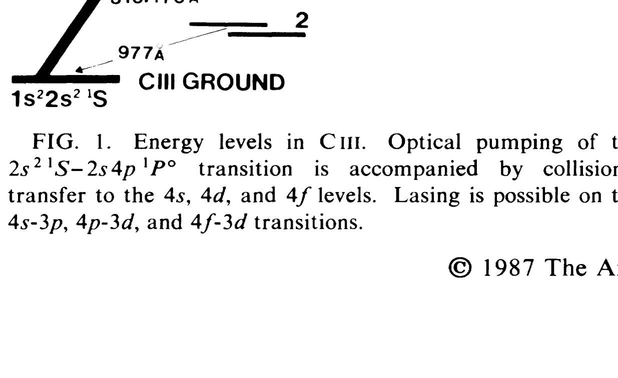

FIG. 1. Energy levels in C III. Optical pumping of the $2s^2\,{}^1S$–$2s4p\,{}^1P^\circ$ transition is accompanied by collisional transfer to the $4s$, $4d$, and $4f$ levels. Lasing is possible on the $4s$-$3p$, $4p$-$3d$, and $4f$-$3d$ transitions.

Many soft-x-ray laser schemes have been proposed[2–5] for resonant photoexcitation in H-like and He-like ions. Recently, a new class of photoexcited lasers was identified[6] in Be-like ions, with laser wavelengths from 2177 Å in C III pumped by Mn VI, to 200 Å in Mg IX pumped by Al XI. The C III–Mn VI scheme was studied as a prototype for such lasers. Fluorescence was measured[7] on several 4-3 transitions in C III. Single-pass gain and multipass amplification (with a resonator) were then measured, as described in this Letter.

Figure 2 is a schematic drawing of the experimental apparatus. The C III ions are produced in a vacuum-arc discharge between a 6-mm-diam carbon cathode and a hollow carbon anode 100 mm away. A discharge is triggered by the focusing of a 15-J, 50-ns CO_2 laser onto the cathode face. The Mn VI pump plasma is produced by the focusing of another 15-J, 50-ns CO_2 laser to a $2\times 23\text{-mm}^2$ line focus on a Mn slab, as shown in Fig. 2. The carbon discharge has a 6.4-kA peak and 60-μs flat-topped duration current as shown in Fig. 3(a). The Mn plasma is produced 36 μs after the carbon discharge is initiated. Intense, enhanced fluorescence is observed[1] in C III at 2163 and 2177 Å, for about 0.5 μs, coincident with the Mn plasma. The first "noise" fiducial (10 μs into the sweep) in Fig. 3(a) shows when the first laser is fired. The later noise fiducial shows that the second laser is fired 36 μs after the first.

In the first experiments, single-pass gain was measured at 2177 and 2163 Å. The front mirror of the laser cavity (labeled A in Fig. 2) was replaced by a lens L_2 (shown in an inset in Fig. 2) which, together with lens L_1, collimated and focused the pumped C III region onto the entrance slit of the uv monochromator. Also, the Brewster windows were replaced by flat, quartz vacuum windows, as shown in the insets of Fig. 2. Over several shots, the

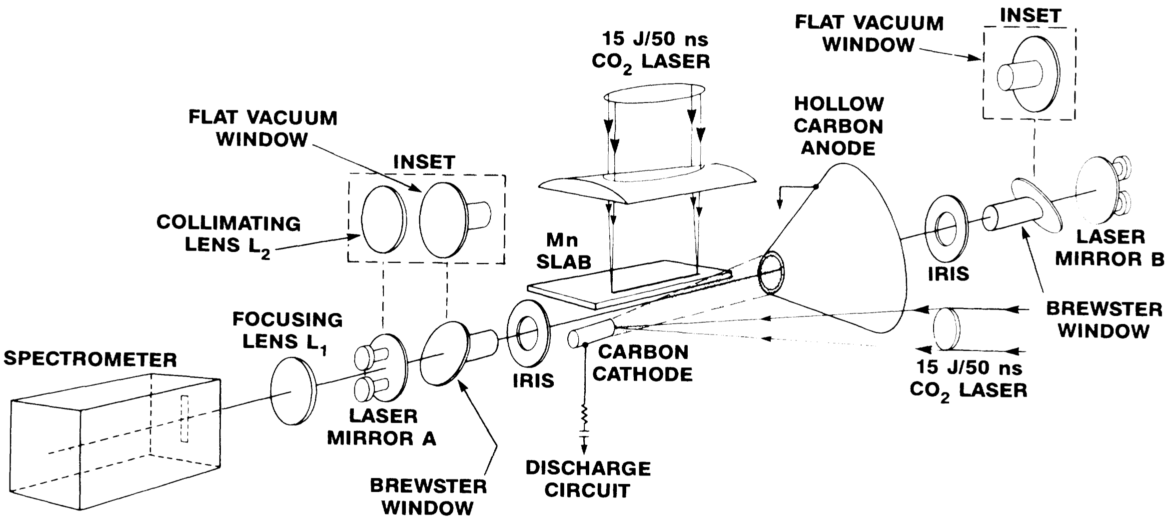

FIG. 2. Schematic diagram of the experimental apparatus.

spontaneous emission and enhanced fluorescence were each measured, with and without the reflecting mirror B. The ratio R of the measured line intensities with and without the mirror is given by

$$R = 1 + se^{-\tau}, \quad (1)$$

where τ is the integrated absorption along the entire optical path length, and s ($=0.5$) is the measured product rt^2, with t the transmittance of the flat, vacuum windows and r the reflectivity of mirror B. For an inverted transition with gain, $\tau < 0$, and $R > 1+s$. At both 2163 and 2177 Å, the measured values of R versus time (during resonant optical pumping) were within $\mp 20\%$ of each other, and R was > 1.5 (implying gain), for about 0.3 μs. A representative plot of the single-pass, gain-length product ($-\tau$) versus time is shown in Fig. 3(b). To corroborate the gain measured at 2177 and 2163 Å, the C II line at 2174 Å was then examined. This C II line was measured to be optically thin ($\tau = 0$) and occurs conveniently close to the two lasing wavelengths. The measured value of R versus time for C II was 1.5, thus verifying the gain on the C III lines. The single-pass, gain-length products shown in Fig. 3(b) are similar to the predictions of a 72-level, collisional-radiative model[1] for photoexcitation. With measured values of electron density ($\approx 10^{16}$ cm^{-3}) and temperature (≈ 4 eV) in the C discharge,[1] populations of $n=3$ and $n=4$ levels were calculated with the use of atomic data provided by Morgan.[8] Photoexcitation was included by our estimating a 20-eV brightness temperature for the Mn VI pump line. The predicted, single-pass gain coefficient was 0.15 cm^{-1} at both 2163 and 2177 Å. For a 23-mm gain length, the predicted, single-pass, gain-length product is thus 0.35, which compares fairly well with the measured values in Fig. 3(b).

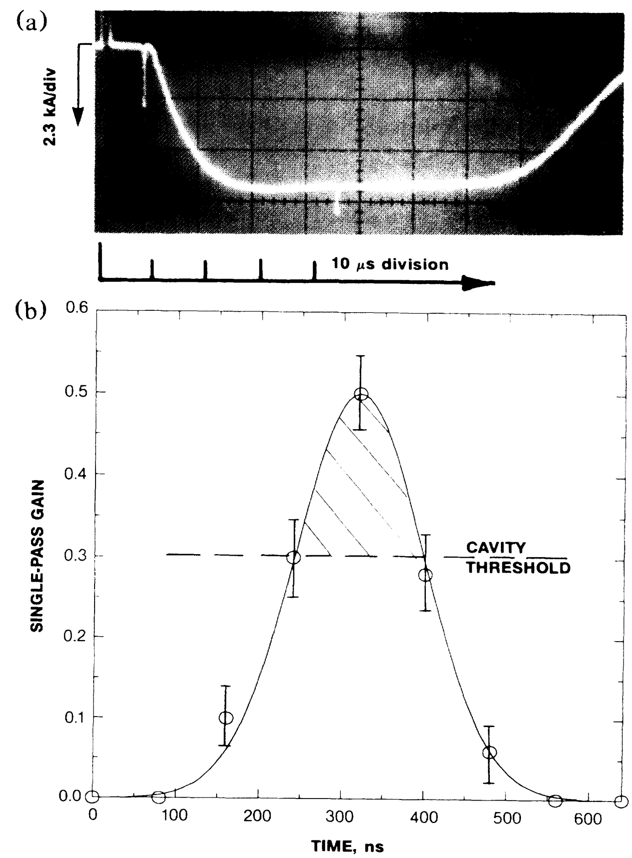

FIG. 3. (a) Current, 2.3 kA/div, vs time. The first noise fiducial (10 μs into the sweep) marks the firing of the first CO_2 laser, to trigger the carbon discharge; the second noise fiducial (36 μs later) marks the firing of the second CO_2 laser, to produce the Mn plasma. (b) Single-pass, gain-length product vs time for the C III 2177- and 2163-Å lines. The dashed horizontal line is the cavity loss threshold of 0.30. Net gain occurs in the shaded region.

To seek laser oscillation at 2177 and 2163 Å, the col-

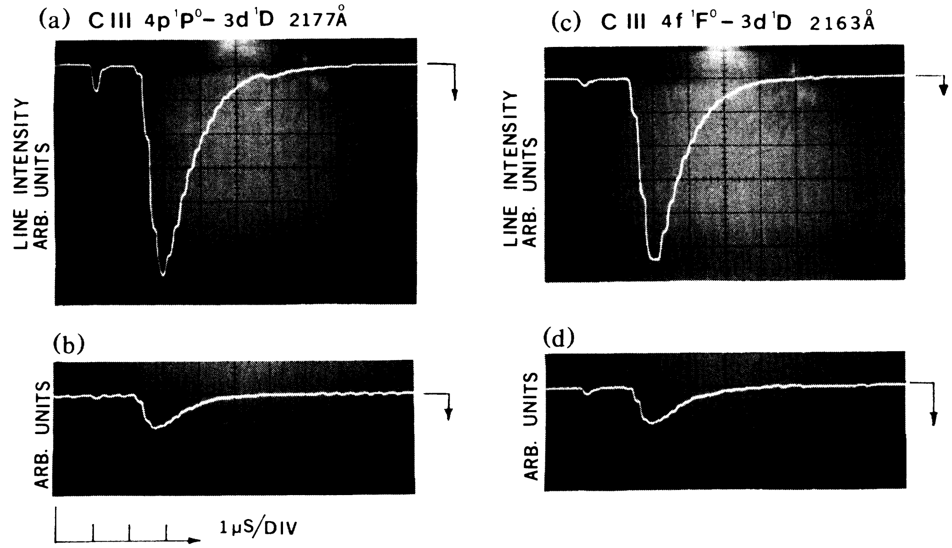

FIG. 4. Evidence for amplification in C III. (a) Emission at 2177 Å, with tuned cavity. (b) Emission at 2177 Å, with the front cavity mirror removed. (c) Emission at 2163 Å, with the tuned cavity. (d) Emission at 2163 Å, with the front cavity mirror removed.

limating lens L_2 (inset in Fig. 2) was replaced by the front mirror A of the Fabry-Perot resonator (Fig. 2), and the flat vacuum windows were replaced by two fused silica Brewster windows, as shown. The transmittance T of these windows began at 96% but decreased to $\approx 90\%$ after just a few discharges. After tens of discharges, the transmittance had decreased to $\approx 80\%$. The decrease was caused by deposition of carbon from the discharge on the vacuum side of the Brewster windows. The cavity threshold, $-\ln(rT^2)$, where r (=92%) is the reflectivity of the laser mirrors, thus increased from 0.165 to 0.53 during a typical experiment, before the Brewster windows were replaced. Since a few discharges had always occurred before any multipass amplification measurements were made, it is assumed that the cavity threshold was ≈ 0.30 (90% transmission) for all the results presented in this Letter. This mean threshold is shown as a horizontal dashed line in Fig. 3(b). The net gain-length product (per pass) is the portion of the gain curve (shown shaded) which is above this threshold. The duration of this net gain is ≈ 0.16 μs, which corresponds to ≈ 50 passes in the 1-m-long cavity. Summation of the net gain-length product per pass over 50 passes gives a total (cavity) gain-length product of ≈ 4.5. With the neglect of gain saturation, this implies that stimulated emission amplifies the fluorescence by a factor of $\exp(4.5) \approx 90$. To detect this enhancement, the ratio of the line intensities with and without the front mirror of the laser cavity was measured. Typical results are shown in Fig. 4. Figures 4(a) and 4(c) show the intensities with the tuned laser cavity at 2177 and 2163 Å, respectively. Figures 4(b) and 4(d) show the intensities with the front mirror A removed. The signals in Fig. 4(b) and 4(d) correspond to a single pass of amplification, whereas the signals in Figs. 4(a) and 4(c) correspond to ≈ 50 passes of amplification, and should therefore be greater. The ratio of these two signals inside the cavity should be $\approx \exp(4.5)/\exp(0.1) \approx 80$. However, because the front mirror A transmits only 8%, the ratio at the detector should be ≈ 6; i.e., the signal with the front mirror A removed should be *lower* by a factor of 6 than that with the tuned cavity. It is assumed in these estimates that the solid angle for detection of the two signals is the same. This was ensured in the experiment by our placing a pair of 5-mm irises 500 mm apart along the optical axis, so that for both spontaneous and stimulated emission, a collimated beam was detected. The signals in Figs. 4(b) and 4(d) are about 5 to 6 times lower than those in Figs. 4(a) and 4(c), confirming multiple-pass amplification and the onset of laser oscillation.

To corroborate these measurements, similar measurements were made on the wings (optically thin) of the C III, $2p^2$-$2s2p$ line at 2297 Å. For such a nonlasing line, the signal with the front mirror A removed should be *higher* than that with the tuned cavity. The measured signal at 2297 Å with the front mirror removed was about 5 times higher than that with the cavity, as expected.[1]

It was suggested that the results of Fig. 4 might be due to radiation at 2177 and 2163 Å from the Mn pump plasma which "walks on" to the cavity, giving an apparent but spurious gain. To check this, the measurements were made with the Mn plasma alone. The measured signals with the mirror removed were about 5 times *higher* than with the cavity; i.e., the results were similar to those at the nonlasing wavelength of 2297 Å. Furthermore, the absolute levels of these signals were much smaller than those with the pumped carbon discharge, and thus did not influence the results of Fig. 4.

The *decrease* in signal with the mirror removed at the laser wavelengths, as opposed to the *increase* in signal at a nonlasing wavelength, is proof of lasing at 2177 and 2163 Å. The purpose of these experiments was to demonstrate a prototype for soft-x-ray amplifiers based on resonant photoexcitation. More powerful and more efficient uv lasers are available by other means. The results described here are theoretically scalable to shorter wavelengths in higher-Z, isoelectronic analogs of C III, such as Mg IX pumped by Al XI and others.[6]

It is a pleasure to acknowledge helpful conversations with Professor W. R. Bennett, Jr., Professor R. K. Chang, and Dr. R. R. Prasad. We are grateful to Professor H. R. Griem for a critical reading of the manuscript. Dr. H. Kilic participated in earlier aspects of this research. This research was supported by U.S. Air Force Office of Scientific Research Grant No. 81-0077. One of us (N.Q.) enjoyed a Gibbs Fellowship from the Yale University Physics Department for a portion of this research.

[a]Present address: Cornell University, Ithaca, NY 14850.
[b]Present address: Physics International Co., San Leandro, CA 94577.

[1]N. Qi, Ph.D. thesis, Yale University, 1987 (unpublished).
[2]P. Hagelstein, Ph.D. thesis, Lawrence Berkeley Laboratory Report No. UCRL 3100, 1981 (unpublished).
[3]A. Vinogradov, I. Sobelman, and E. Yukov, Krantoraya Elektron. (Moscow) **2**, 105 (1975) [Sov. J. Quantum Electron. **5**, 59 (1975)].
[4]B. Norton and N. Peacock, J. Phys. B **8**, 6 (1975).
[5]J. Apruzese, J. Davis, and K. Whitney, J. Appl. Phys. **53**, 4020 (1982).
[6]M. Krishnan and J. Trebes, Appl. Phys. Lett. **45**, 189 (1984).
[7]N. Qi, H. Kilic, and M. Krishnan, Appl. Phys. Lett. **46**, 471 (1985).
[8]W. L. Morgan, private communication.

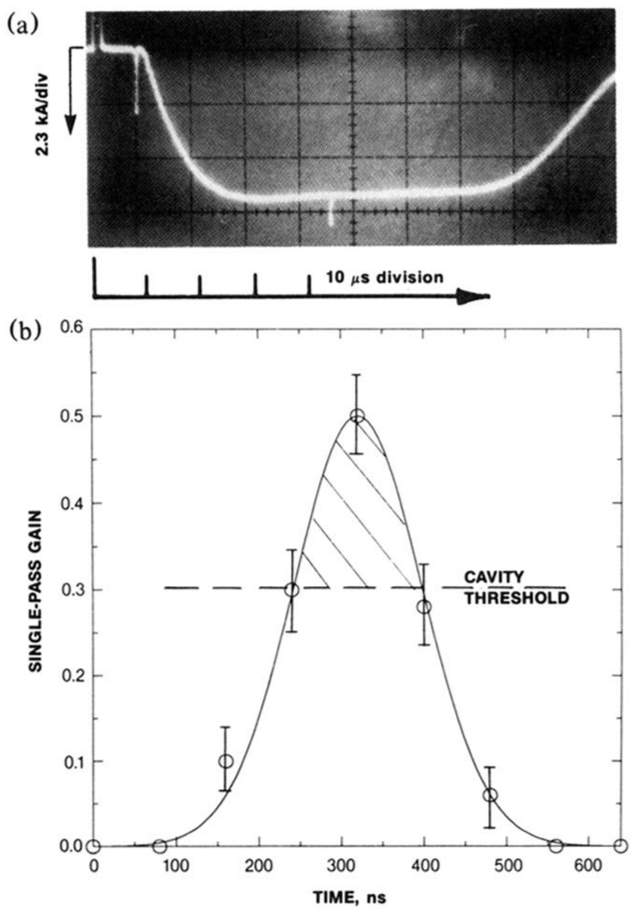

FIG. 3. (a) Current, 2.3 kA/div, vs time. The first noise fiducial (10 μs into the sweep) marks the firing of the first CO_2 laser, to trigger the carbon discharge; the second noise fiducial (36 μs later) marks the firing of the second CO_2 laser, to produce the Mn plasma. (b) Single-pass, gain-length product vs time for the C III 2177- and 2163-Å lines. The dashed horizontal line is the cavity loss threshold of 0.30. Net gain occurs in the shaded region.

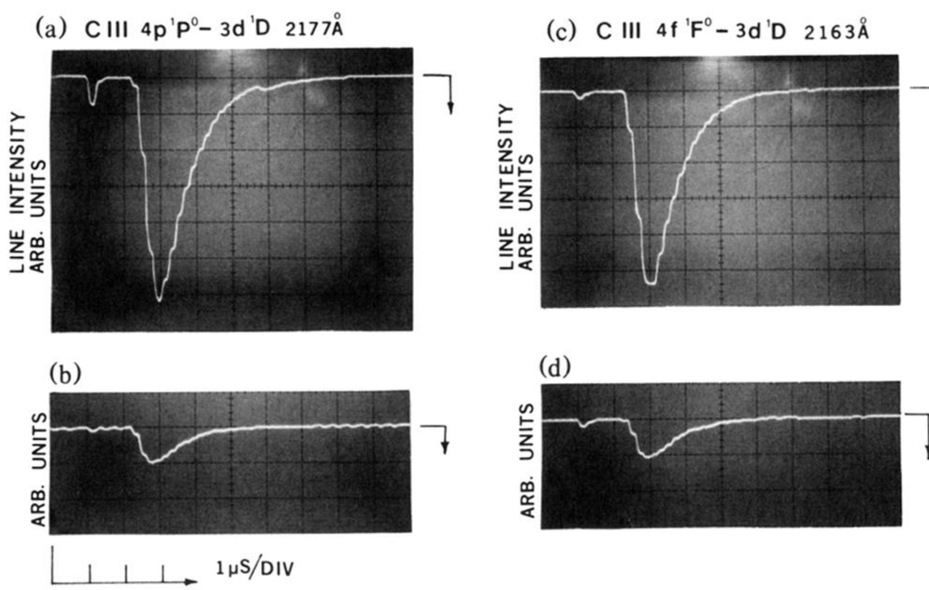

FIG. 4. Evidence for amplification in C III. (a) Emission at 2177 Å, with tuned cavity. (b) Emission at 2177 Å, with the front cavity mirror removed. (c) Emission at 2163 Å, with the tuned cavity. (d) Emission at 2163 Å, with the front cavity mirror removed.