Soft X-Ray Amplification at 26.2 nm with 1-Hz Repetition Rate in a Table-Top System

D. Korobkin, A. Goltsov,* A. Morozov, and S. Suckewer
Princeton University, Princeton, New Jersey 08544
(Received 4 May 1998)

Using a very small Nd/YAG pumping laser (0.45 J in 8 nsec), we have demonstrated high gain ($G \approx 14-19$ cm^{-1}) and gain-length product ($GL \geq 5$) in hydrogenlike B V ions at a wavelength of 26.2 nm (the 3-2 transition) at a repetition rate of 1 Hz. The preplasma in a B_2O_3 microcapillary was created from wall ablation with a 0.2-J (in 20 nsec) KrF laser. The gain was generated in the microcapillary plasma in a traveling wave regime by longitudinal pumping. This very efficient soft x-ray lasing system takes up less space than is available on a 4 ft × 10 ft optical table. [S0031-9007(98)06919-1]

PACS numbers: 42.55.Vc, 32.80.Rm, 42.65.Dr, 52.40.Nk

In the last ten years we have put a significant amount of effort into the development of a very compact soft x-ray laser (SXL). A number of researchers working on the development and the applications of x-ray lasers have pursued a similar idea (see, e.g., Refs. [1–6]). We concentrated our research on the use of a fast recombining plasma of SXL media (see, e.g., Refs. [7,8]). Although we have demonstrated quite a high gain $G \approx 5-7$ cm^{-1} in the past, we could not achieve a gain-length product $GL \geq 4.5$ which would be unequivocal proof of the gain (for such GL, for which the ratio of stimulated emission to spontaneous emission is larger than 10, the error in lasing line intensity measurements in SXL experiments becomes sufficiently small to be confident in the correctness of the gain).

The most promising results were obtained in a fast recombining plasma inside a microcapillary [9]. Carbon plasma was created by the ablation of the polyethylene microcapillary walls either by a prepulse or by the front of the laser pulse, while the main pulse heated the plasma to temperatures at which carbon atoms were totally stripped of electrons. After the laser pulse the plasma was cooled very rapidly thus fast recombining providing a lasing medium. The optimum microcapillary diameter was experimentally established to be 350 μm. The Nd/glass laser (2–5 J, 1.5 nsec) was focused at the entrance of the microcapillary to a spot diameter of 40–50 μm (beam power density in the range $5 \times 10^{13}-2 \times 10^{14}$ W/cm^2) and propagated in a 10–15 mm long microcapillary plasma, where good channeling conditions were created. By comparing ratio of intensities of hydrogenlike ions CVI 18.2 nm (3-2 transition) and CVI 13.5 nm lines (4-2 transition) in the axial and transverse directions with an increasing 18.2 nm line in the axial directions about 25 times with respect to the 13.5 nm line, we concluded that the gain-length product, GL, reached ~5. Unfortunately this gain was not reproducible, and it was not possible to confirm this gain by measuring the 18.2 nm line intensity versus plasma length. An effort to improve the reproducibility of the results was unsuccessful. The main reason for the irreproducibility of the gain in the polyethylene microcapillary seems to be the irreproducibility of the initial plasma ("preplasma") in which the main laser pulse propagates. This shot-to-shot preplasma irreproducibility was observed using a CCD camera (time integrated pictures). We have tried to eliminate this irreproducibility in the polyethylene microcapillaries by creating the preplasma with a second laser or high voltage discharge. By providing large delays (up to 10 μsec) between the time of creation of the preplasma and the pumping laser pulse we were able to improve the reproducibility of the plasma conditions during gain generation. However, at such large delay times the radial distribution of the plasma density was no longer favorable for propagation of the pumping laser beam.

Success came quite unexpectedly in a very different experiment during the preparation of two lasers to generate a gain at 4.8 nm in B V ions in the microcapillaries. During the alignment of the B_2O_3 microcapillary, we compared soft x-ray spectra in the vicinity of hydrogenlike B V 4.8 and 4.1 nm lines from 2-1 and 3-1 transitions (transitions to ground state), respectively (see Fig. 1). Spectrum in Fig. 1 was obtained for a microcapillary $L =$ 1 mm long with bore diameter $\phi = 0.35$ mm and with an exposure of 5 shots. The delay time between the KrF laser (prepulse) and Nd/YAG laser (pumping pulse) was $\Delta t = 400$ nsec. We may see that the H-like B V ion lines are much stronger than the He-like B IV ion lines, which is an appropriate condition for the generation gain in B V. More importantly, the B V 4.1 nm line (3-1 transition) is stronger than the resonance B V 4.86 nm line (2-1 transition), although the ratio of spontaneous rate coefficients for these lines is $A_{21}/A_{31} \approx 8.3$ ($A_{21} \approx 2.9 \times 10^{11}$ sec^{-1}). Because of the proximity of these two lines, we can assume the same spectrometer sensitivity for both of them. The intensity ratio of these lines hinted at a population inversion between levels 3 and 2 with the possibility of gain for B V 26.2 nm line (3-2 transition). Hence, an experiment was arranged to measure the gain in microcapillary plasmas of different lengths.

The experimental setup is shown in Fig. 2. A low power 1 Hz KrF laser (248 nm, 0.2 J, 20 nsec) was

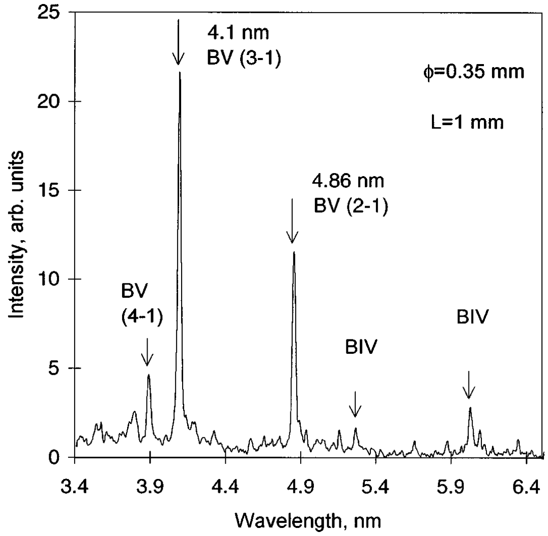

FIG. 1. Spectra in the vicinity of 4.1 and 4.86 nm B V lines for $L = 1$ mm long and 0.35 mm diameter microcapillary. Delay time of 0.45 J, 8 nsec Nd/YAG laser with respect to 0.2 J, 20 nsec KrF laser was $\Delta t = 400$ nsec.

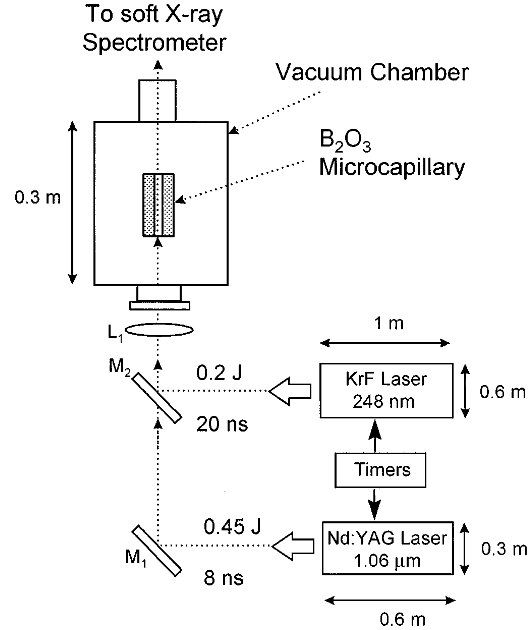

FIG. 2. Schematic of experimental arrangement for generation gain at 26.2 nm in B V ions in B_2O_3 microcapillaries; KrF laser (0.2 J) creates initial plasma, which is further ionized (pumped) by 0.45 J Nd/YAG laser at 1-Hz repetition. The horizontal dimensions of major components are indicated.

focused (not tightly) with a $f = 30$ cm lens (rectangular beam 2.5 cm $\times$ 1 cm) on the entrance of a microcapillary. Microcapillaries of lengths from 1 to 4 mm and diameters from 0.25 to 0.45 mm were made in B_2O_3. After delay time, Δt (Δt was varied between 100 and 1200 nsec), the second, low energy Nd/YAG laser (0.45 J, 8 nsec) was fired (1-Hz repetition rate). The Nd/YAG laser was tightly focused with the same $f = 30$ cm lens (beam diameter $\sim$1 cm) onto the plasma at the entrance of the microcapillary providing a power density $\sim 2 \times 10^{13}$ W/cm^2. The Nd/YAG laser beam was directed to the microcapillary by a near 100% reflective mirror, M_1, and the KrF laser beam was directed by a mirror, M_2, which was transparent for the 1.06 μm wavelength of a Nd/YAG laser. For the measurements of the transmission of beam energy through the microcapillary plasma an energy detector was used. The detector was calibrated and placed just behind the microcapillary on the path to SX spectrometer. In Fig. 2 the horizontal dimensions of both lasers and vacuum chamber are shown. It can be seen that the whole soft x-ray laser system (without spectrometer and other diagnostics) easily fits on a 4 ft $\times$ 10 ft optical table.

We would like to stress the major differences between the present system and the system for 13.5 nm SXL [10]. Although the 13.5 nm SXL is quite a compact system (2 optical tables) it requires very high intensity and a very short pulse pumping laser in order to create gain in transition to ground state ($n = 1$). The crucial feature of such a system is that it provides good scaling to much shorter wavelength x-ray lasers. In contrast, the system presented here provides lasing action between two excited levels ($n = 3$ and 2) of H-like B V ions. Because radiative transition between these levels is about an order of magnitude slower than the transition to ground level, and because a population inversion can exist between them even if the population of the ground level is 2–3 orders of magnitude higher than population of these excited levels, the pumping laser pulse can be relatively long (in nsec range). This makes it possible to use a low power (therefore very compact and quite inexpensive) pumping laser.

The soft x-ray spectra were recorded, as in our work on the development of a 13.5 nm laser in Li III ions [10], with a 2 m, high resolution grazing incidence spectrometer [11]. A microchannel plate detector, MCP, was gated for 10 nsec and synchronized with Nd/YAG laser pulses. As in all our works with microcapillaries, the crucial task was the very precise alignment of the axis of the microcapillary with the optical axis of the spectrometer and laser beams.

In Fig. 3 are shown spectra in the vicinity of the 26.2 nm line for three different microcapillary lengths ($L = 1$, 2, and 3.5 mm) obtained for the same conditions as the spectrum in Fig. 1. It is clear that the B V 26.2 nm line intensity is rapidly increasing with microcapillary length L, whereas other lines (e.g., O III line) increase approximately proportional to the microcapillary length (see Fig. 4). In the spectra a large number of oxygen (mostly O III and O IV) lines exist due to oxygen concentration in microcapillary walls (B_2O_3). Although the lasing line is much brighter than the oxygen lines, the larger exposure of the oxygen lines over space and time cause their intensities to be significant.

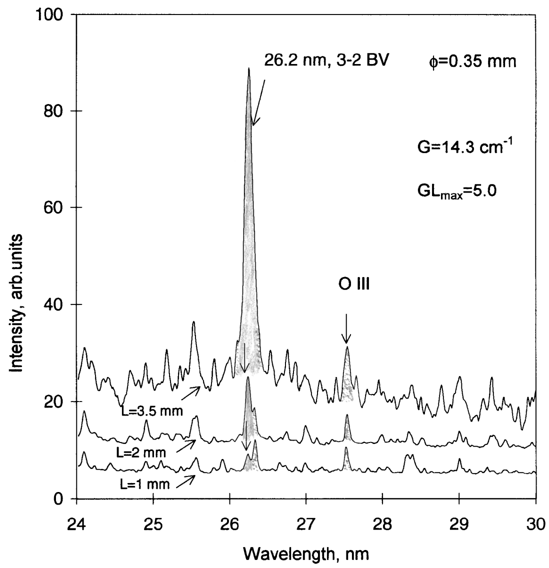

FIG. 3. Spectra in the vicinity of B V 26.2 nm line for $L = 1$, 2, and 3.5 mm long, 0.35 mm diameter B_2O_3 microcapillaries. Laser and plasma conditions as in Fig. 1.

In Fig. 4 each point corresponds to an exposure of five shots. Points for 26.2 nm line were fitted by a least squares method with the Linford formula [12], indicating gain $G \approx 14.3\ \text{cm}^{-1}$ and gain-length (max length) product $GL \approx 5$. Slightly higher gain ($G \approx 19\ \text{cm}^{-1}$) was obtained in another series of experiments at similar experimental conditions as in Fig. 3, but for only two microcapillary lengths $L = 1.5$ and 3 mm with $GL \approx 5.7$. Improvement of the gain was probably related to the better alignment of the microcapillary. We also observed that usually higher gain could be generated in shorter microcapillaries.

By increasing the diameter of the microcapillary ($\phi \approx 0.45$ mm) the gain could be generated more uniformly in a longer microcapillary (up to $L = 4$ mm), but its value decreases ($G \approx 12.1\ \text{cm}^{-1}$) and the gain-length product drops below 5.

With decreasing the diameter of the microcapillary ($\phi \approx 0.25$ mm) we did not succeed in generating gain for $L \geq 2$ mm. Although we were able to generate gain $G \approx 26\ \text{cm}^{-1}$, but only up to a 1.7 mm long microcapillary ($GL \approx 4.4$). We expect that high gain will be possible in a microcapillary with a diameter of 0.25 mm diameter and a length longer than 2 mm, by decreasing the diameter of the focal spot of the Nd:YAG laser beam.

Presently our main concern is about increasing the gain-length product for 26.2 nm radiation. In order to increase population inversion, and hence a gain, G, we will increase the pumping energy of the Nd/YAG laser from 0.45 to about 1 J (such a laser is being constructed in our laboratory). However, with increasing the pumping energy of the Nd/YAG laser beam, the propagation in a microcapillary may worsen at longer time delays between the prepulse and pumping pulse (Δt) even in larger diameter microcapillaries. For example, for delay $\Delta t = 800$ nsec, the propagation (transmission) of Nd/YAG laser beam energy in the microcapillary ($L = 4$ mm, $\phi = 0.45$ mm) decreases with increasing the beam power (energy) as can be seen in Fig. 5. Therefore it will be necessary to use a shorter Δt. For $\Delta t = 120$ nsec the beam propagation is improved with increasing beam power. Unfortunately at this shorter delay time the plasma density in the microcapillary was usually too high for the creation of high population inversion between levels 3 and 2 (electron collisions tend to equilibrate population between these levels). However, we found

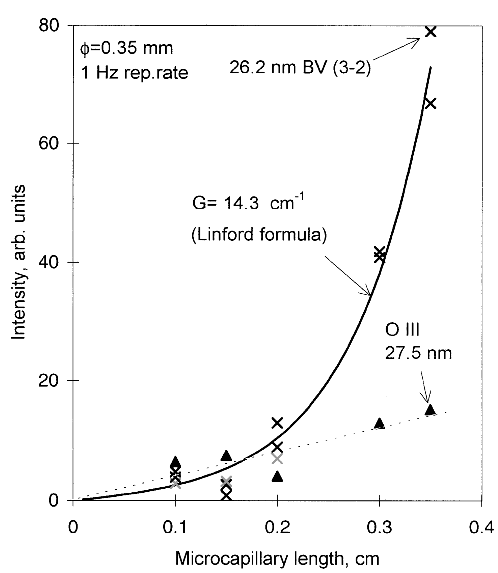

FIG. 4. Intensity of B V 26.2 nm and O III 27.5 nm lines as a function of microcapillary length for experimental conditions as in Figs. 1 and 3.

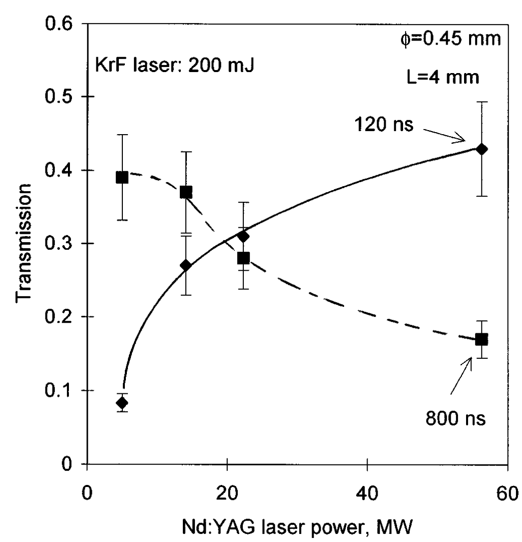

FIG. 5. Nd/YAG laser beam propagation (transmission) through $L = 4$ mm long and 0.45 mm diameter microcapillary as a function of laser power for plasma created by 0.2 J KrF laser and two delay times ($\Delta t = 120$ and 800 nsec).

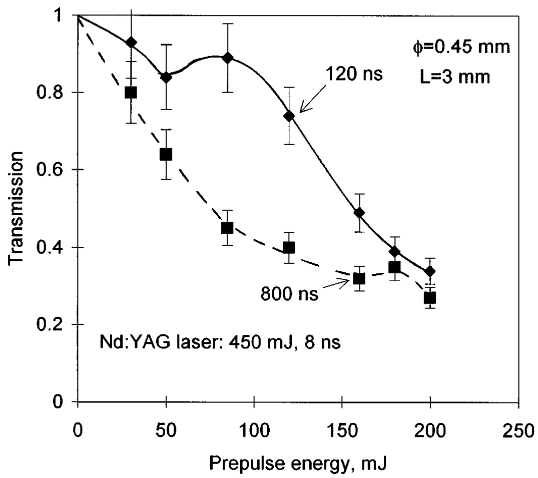

FIG. 6. Nd/YAG laser beam (0.45 J, 8 nsec) propagation (transmission) through $L = 3$ mm long and 0.45 mm diameter microcapillary as a function of prepulse energy (KrF laser energy) for two delay times ($\Delta t = 120$ and 800 nsec).

out (see Fig. 6) that by decreasing the energy of prepulse (from the KrF laser) we can improve the propagation of a laser beam due to the lower initial plasma density. As it can be seen in Fig. 6, for prepulse energy ~100 mJ about 80% of Nd/YAG laser beam energy propagates through a $L = 3$ mm long microcapillary plasma at $\Delta t = 120$ nsec, whereas only 40% of the beam energy propagates at 800 nsec. This decrease of the beam propagation ability may be related to the flattening of the electron density distribution along the plasma radius, hence decreasing the plasma focusing effect. From these measurements it becomes quite clear that with increasing pumping beam power we will have to optimize prepulse beam energy and delay time, Δt, in order to maximize the propagation length of the pumping beam, hence maximizing GL for 26.2 nm radiation.

The data about laser beam propagation will be useful for theoretical modeling (under development) which is crucial for better understanding of our result and scaling to higher gain.

In conclusion, we demonstrated, for the first time, lasing action at wavelength below 30 nm at 1 Hz repetition rate in a very compact system ("table top soft-x-ray amplifier"). Lasing action took place in a microcapillary plasma at 26.2 nm from 3-2 transition in hydrogenlike B V. Gain $G \approx 14$ cm^{-1} and gain-length product $GL \approx 5$ was measured for 0.45 J in 8 nsec pumping laser beam and 0.2 J in 20 nsec laser created plasma in microcapillary (the maximum GL up to 5.7 was also measured). Measurements of laser beam propagation in the microcapillary plasma indicated that by optimizing the energy of the laser beam for creation of the plasma and the delay of pumping beam and by increasing by approximately a factor of 2 the energy of the pumping beam it will be possible to significantly increase the gain-length product.

The importance of this new result is that it is possible to use a very low power pumping laser to demonstrate a reproducible high gain-length product in very compact, and relatively inexpensive systems at such short wavelength.

We thank N. Tkach for his dedication to the experiments, help with electronics, and machining of various parts of the system, and Dr. V. Sokolov (TRINITI, Russia) for help at the earlier stage of the experiment. We also thank Professor R. Miles for lending us the Nd/YAG laser, which was crucial for this experiment, and Dr. G. Dansereau (U.S. Borax Inc.) for providing us with B_2O_3 powder. This work was supported by NSF Grant No. ECS-9726310.

*Permanent address: Kurchatov Institute, TRINITI, Troitsk, Russia.

[1] B. E. Lemoft, G. Y. Lin, C. L. Gordon III, C. P. Barty, and S. E. Harris, Phys. Rev. Lett. **74**, 1574 (1995).
[2] J. J. Rocca, V. N. Shylaptsev, F. G. Tomasel, O. D. Cortazar, D. Hartshorn, and J. L. Chilla, Phys. Rev. Lett. **73**, 2192 (1994).
[3] J. Goodberlet, T. Savas, and P. L. Hagelstein, in *Proceedings of the SPIE Conference on Soft X-Ray Lasers and Applications*, edited by J. Rocca and P. Hagelstein (SPIE, Bellingham, WA, 1995), Vol. 2520, p. 191.
[4] P. V. Nickles *et al.*, in *Proceedings of the SPIE Conference on Soft X-Ray Lasers and Applications* (Ref. [3]), p. 373.
[5] H. M. Milchberg and C. G. Durfee III, in *Proceedings of the SPIE Conference on Soft X-Ray Lasers and Applications* (Ref. [3]), p. 209.
[6] J. Dunn *et al.*, in *Proceedings of the SPIE Conference on Soft X-Ray Lasers and Applications II*, edited by J. Rocca and L. DaSilva (SPIE, Bellingham, WA, 1997), Vol. 3156, p. 114.
[7] D. Kim, C. H. Skinner, G. Umesh, and S. Suckewer, Opt. Lett. **14**, 665 (1989); also C. H. Skinner *et al.*, J. Opt. Soc. Am. B **7**, 2042 (1990); also C. O. Park, L. Polonsky, and S. Suckewer, Appl. Phys. B **58**, 19 (1994).
[8] S. Suckewer and C. H. Skinner, Comments At. Mol. Phys. **30**, 331 (1995).
[9] A. Morozov, L. Polonsky, and S. Suckewer, in *Proceedings of the 2nd International Symposium "Plasma '95," Warsaw, 1995* (Centrum Badan Kosmicznych, PAN, Warsaw, 1995), Vol. 2, p. 247.
[10] D. Korobkin, C. H. Nam, A. Goltsov, and S. Suckewer, Phys. Rev. Lett. **77**, 5206 (1996).
[11] J. L. Schwob, A. Wouters, and S. Suckewer, Rev. Sci. Instrum. **58**, 1601 (1987).
[12] G. L. Linford, E. R. Pesessin, W. R. Sooy, and M. L. Spaeth, Appl. Opt. **13**, 379 (1974).