Recent Achievements in Soft-X-Ray Lasing

The Nova laser facility has permitted longer, more powerful laser amplifiers. Using our current exploding-foil target concept, we have observed new lasing transitions, shorter x-ray wavelengths, and power at the megawatt level.

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In 1984, we made the first-ever unambiguous demonstration of soft-x-ray lasing in the laboratory, at wavelengths of 20.6 and 20.9 nm, using an optical-laser-pumped amplifier.[1,2] Following this accomplishment, we have focused our efforts on adapting our experimental setup to the new two-beam Nova target chamber and on designing new and more informative diagnostics. The second phase of our laboratory x-ray lasing research began in October 1985 as the two-beam Nova target chamber became operational.

In our most recent experiments, we have observed some of the lasing transitions that had been predicted but not previously observed, amplification at wavelengths as short as 10.6 nm, and saturated output power from the selenium laser (20.6 and 20.9 nm) at power levels of 1 MW or greater (175 ps FWHM).

New Transitions

We have made a definite observation of the neon-like $3p$–$3s$ (J = 0–1) transition at 18.24 nm that was not conclusively observed in our original work, presumably since its gain was much smaller than expected. Figure 1 illustrates the spectrum of lasing transitions obtained for neon-like selenium. The 20.6- and 20.9-nm J = 2–1 transitions extend off scale in this figure to show the three weaker transitions at 18.24 nm (J = 0–1), 22.03 nm (J = 1–1), and 26.23 nm (J = 2–1). The 18.24-nm transition is now easily identified since there are no spontaneous transitions powerful enough to obscure the spectrum. For reasons still not yet determined, the estimated gain of this transition (~1/cm) is much smaller than originally predicted.

Figures 2 and 3 illustrate our newest results: scaling of the neon-like inversion scheme to the higher Z systems of yttrium and molybdenum. Amplification of the J = 2–1 transition at 15.5 nm in neon-like yttrium (Fig. 2) has been previously noted, but only now is it seen to completely dominate the spectrum. This is possible because, with the Nova laser, we can use targets that are two to three times longer than those feasible with the Novette laser.

With neon-like molybdenum (Fig. 3), we observed amplification of x-ray lines down to approximately 10.6 nm, the shortest wavelength achieved to date. Perhaps more important, though, these results

suggest that amplification using the exploding-foil concept[3] may be more efficient than we originally thought possible.

Shorter Wavelengths

We are now designing a neon-like silver amplifier that we hope will demonstrate lasing at wavelengths as short as 8 nm. Lasing at significantly shorter wavelengths should be possible when we conduct these experiments with the even more powerful ten-beam Nova laser. However, we do not anticipate that even ten Nova beams will produce enough power to create an inversion in a neon-like ion with transitions at wavelengths as short as 3 to 4 nm, our ultimate goal.

Achievement of this goal will require us to develop other, more efficient mechanisms for producing population inversions. Two schemes currently being considered are collisional excitation in nickel-like ions and three-body (electron-electron-ion) recombination in hydrogen-like ions.

The nickel-like system is similar to the neon-like system, except that it uses $4f,4d$ to $4d,4p$ transitions (that is, transitions from the next larger atomic orbitals). The quantum efficiency of this scheme is inherently greater than the neon-like system because there are larger energy differences among the atomic states of the $n = 4$ orbital. Therefore, there is potentially a greater energy output for essentially the same energy invested. We have already begun research on a nickel-like gadolinium scheme wherein we predict that lasing may occur at wavelengths as short as 6.7 nm but more likely at about 10 nm.

Several years earlier, we did some research on recombination laser schemes.[4,5] Recently, we have begun to seek new ways to produce amplification with this inversion mechanism. We earlier reported amplification of the hydrogen-like oxygen $n = 3$–2 transition at 10.24 nm,[4] and we are now attempting to observe it with a much longer amplifier. Most predictions of gain

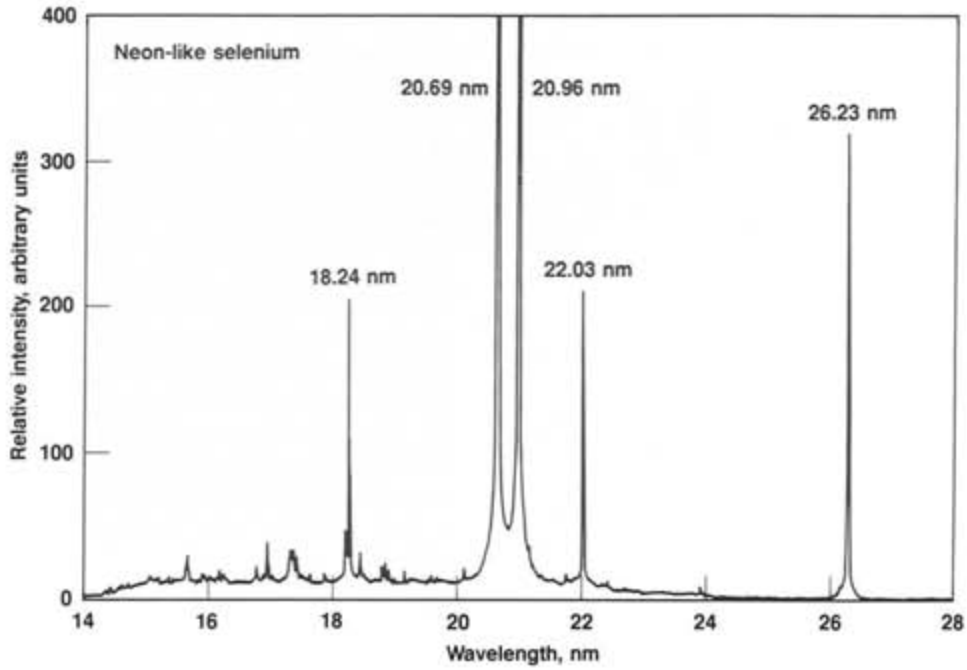

Fig. 1

Lasing spectrum for neon-like selenium in which the line at 18.24 nm for the $3p$–$3s$ ($J = 0$–1) transition is clearly visible. This transition was predicted but not observed in our original work. The more intense 20.69- and 20.96-nm transitions extend off scale to enhance the low-level spectral detail.

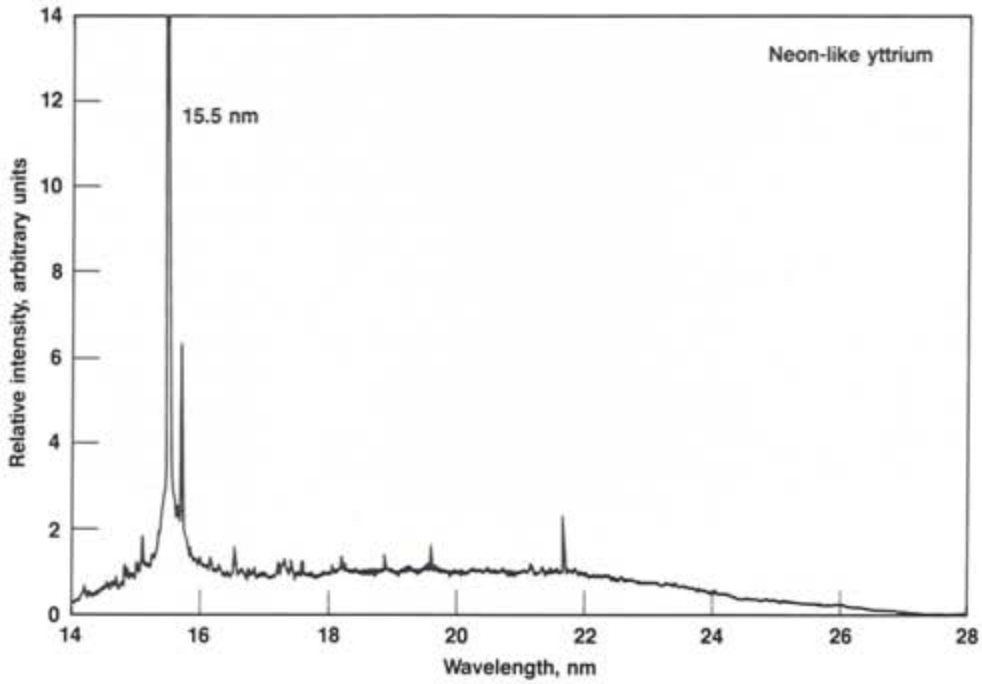

Fig. 2

Lasing spectrum for neon-like yttrium demonstrating scaling of the neon-like inversion scheme to higher Z systems. Amplification of the 15.5-nm $J = 2$–1 transition was made possible by our use of amplifiers two to three times longer than those feasible in our previous work with the less powerful Novette laser.

with this scheme have been relatively small (on the order of 1/cm) as compared with those associated with the neon-like (J = 2–1) transition (gain of about 4 to 5/cm). However, there may be some benefit to the longer time scale over which the amplifier is active in the recombination approach (many nanoseconds, compared with 200 to 300 ps in neon-like ions). To take advantage of the efficiency of multipass amplifier designs, we need enough time to allow many passes of the x-ray laser beam back and forth through the amplifier. This amounts to increasing the amplification lifetime to about 2 to 3 ns for current amplifier geometries.

Saturated Output

Another important goal of our x-ray lasing research has been to achieve a saturated output (that is, conditions wherein there is no longer an exponential growth in signal strength with amplifier length) with the selenium x-ray amplifier. At the ~5/cm gain coefficient for the selenium 20.6- and 20.9-nm lines measured last year with the Novette laser, we found that we needed to produce amplifiers at least 5 cm long. With the two beams of the Nova laser, we can use amplifiers up to 5.2 cm in length, and recent measurements are indicating that we are, indeed, approaching a saturated output. Preliminary analysis of the intensity vs length measurements indicates that power levels for the 4- to 5-cm length are attaining levels of 1 MW or more. We predict that saturation will occur at about 10 MW.

We have developed a special new diagnostic instrument to give more accurate energy measurements at these high output powers. This new diagnostic uses a grazing-incidence mirror and an aluminum filter to view a narrow wavelength region centered at about 20.0 nm. With this instrument, we can take pictures of the x-ray laser beam footprint at 140 cm from the output end, or we can use an x-ray diode to determine the absolute energy in the x-ray beam. These measurements, coupled with other data, allow us to characterize the x-ray laser beam's divergence, pointability, and output power.

In our previous work, the primary diagnostic was the microchannel-plate grazing-incidence spectrometer (MCPIGS),[1] a high-resolution spectrograph that is actually too sensitive to give accurate readings in this high-power range of our latest experiments. In addition, whereas the MCPIGS samples only a segment of the x-ray laser beam, with our new diagnostic instrument, we are able to measure the output power in the entire laser beam.

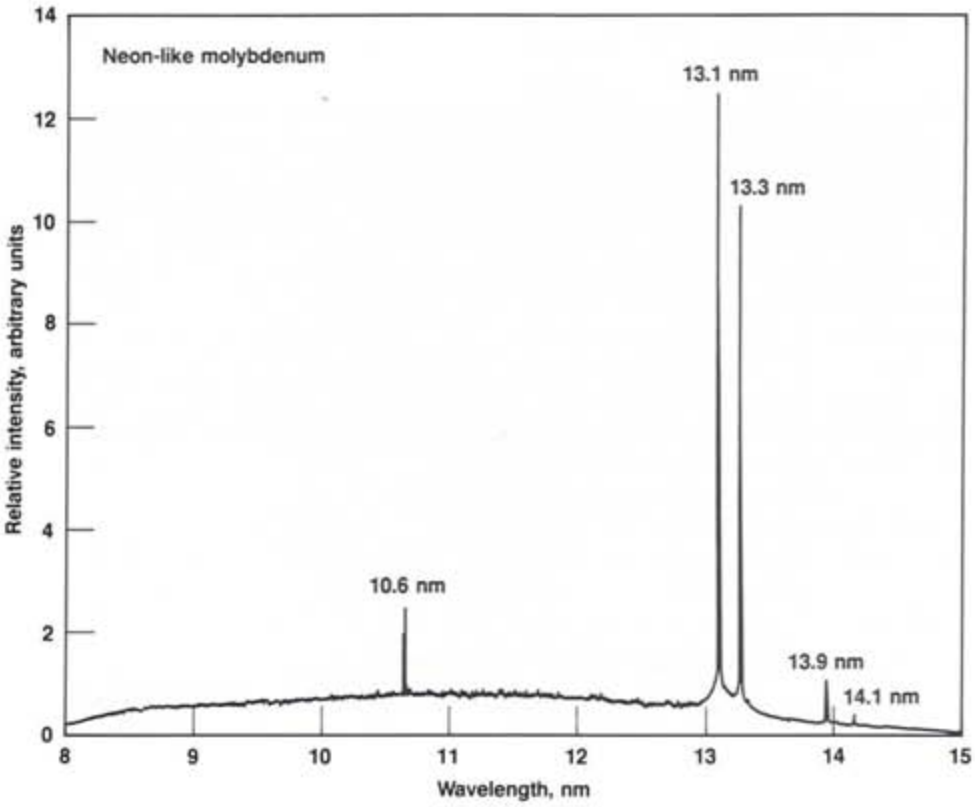

Fig. 3

Lasing spectrum for neon-like molybdenum, another higher Z system. With the more powerful (longer) amplifiers, we have observed x-ray lasing lines as short as 10.6 nm, suggesting that the exploding-foil amplifier concept may be more efficient than we originally thought.

Future Directions

Still to come are experiments to better our understanding of the relevant inversion kinetics, to demonstrate amplification using a multipass x-ray amplifier with normal-

incidence multilayer mirrors,[1] and to demonstrate important applications of the soft-x-ray laser. The significant application of producing three-dimensional images (that is, x-ray holograms) of living cellular material must await development of lasers with wavelengths as short as 3 to 4 nm. Achieving this is one of our major long-term goals.

Key Words: laser—Nova, x-ray; micromechanics—soft-x-ray.

Notes and References

1. See the November 1985 issue of *Energy and Technology Review* (UCRL-52000-85-11) for an overview of the Laboratory's work on soft-x-ray lasing; a description of the microchannel-plate grazing-incidence spectrometer (MCPIGS) is given on pp. 26–28; see pp. 33–34 for a brief discussion of multipass amplification using multilayer mirrors.
2. D. L. Matthews, *Phys. Rev. Lett.* **54**, 110 (1985).
3. M. D. Rosen *et al.*, *Phys. Rev. Lett.* **54**, 106 (1985).
4. D. L. Matthews *et al.*, *Appl. Phys. Lett.* **45**, 226 (1984).
5. D. L. Matthews *et al.*, in *Topical Meeting on Laser Techniques in the Extreme Ultraviolet*, AIP Conference Proceedings (American Institute of Physics, New York, 1984), No. 119, p. 25.