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Driven by High Power Optical Lasers

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Progress and Prospects for Soft X-ray Lasing
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Abstract

We will describe our optical laser pumped XUV Laser Program. To date, we have concentrated our efforts on exploding foil amplifier designs using Ne-like $n=3p$ to $3s$ inversion schemes. We will describe our latest modeling results as well as measurements which demonstrate output power near the 1 MW level at 206 and 209 Å and lasing at wavelengths as short as 106 Å.

Introduction

We have previously demonstrated¹ lasing at 206 and 209 Å using a specially-designed² Se exploding foil amplifier and the Novette Laser Facility as a pump source. Since our original description and demonstration considerable progress has been made in the understanding of the amplification process as well as the amount of power we can produce and the number of elements we can make lase.

In this article, we review the status of our theoretical understanding of the Ne-like Se, Y and Mo laser schemes. We also discuss some pitfalls and successes likely to occur as we proceed toward our ultimate goal: sub 40 Å lasing with a fully-coherent x ray laser beam emitting at multi-MW power levels. We also will review some of our latest experimental facilities and results.

Theory

The exploding foil amplifier design² provides a nearly uniform temperature (~ 0.8 keV electron temperature) and density ($\sim 3 \times 10^{20}$ electrons/cm³) cylindrical plasma within which the x ray laser propagates. The Grotrian diagram illustrating the Ne-like Se energy states, the x ray laser lines and their estimated gain/cm is shown in Fig. 1. The Ne-like $n=3$ levels are principally populated by electron excitation from the $n=2$ ground state, and by dielectronic (three body and radiative also, although to a lesser extent) recombination plus radiative cascades from F-like ions. The population inversion is not produced by selective population mechanisms but by selective radiative decay, the $3p-2p$ transitions being dipole forbidden while the $3s-2p$ are not.

Originally, the population method in this Ne-like scheme had been thought²⁻⁴ to be dominated by electron monopole excitation ($J=0$ to $J=0$) from the Ne-like ground state which would have greatly favored observation of the 182.42 Å $J=0$ to 1 x ray laser transition. In our

previous experiments¹ this was not observed since this transition was not even strong enough to be identifiable. Indeed, our observation¹ of strong amplification of the J=2-1 transitions at 206.3 and 209.6 Å has cast doubt on the simple collisional excitation population mechanism. A summary of the basic discrepancy between experiment on Novette and theory at that time is the low gain observed on J=0 to 1 line, its gain is less than 1 cm^{-1} as compared to predicted numbers of $\sim 10 \text{ cm}^{-1}$, and a higher than predicted gain on the J=2 to 1 transitions, gain is 5.5 to 6.0 cm^{-1} compared to predicted values of 3 to 4 cm^{-1} .

A considerable fraction of our theoretical work since the Novette experiments has been spent on trying to unravel the reasons for the discrepancy between predicted and measured gain in the Ne-like Se amplifier. Our previous theoretical modeling contained at least one important omission. We included dielectronic recombination from the ground-state of F-like to the ground-state of Ne-like and so forth for other adjacent members of the isoelectronic sequences. We used a reasonable approximation to the total rate for this process as determined from matching relative intensities of lines from neighboring charge-states in theoretical versus experimental n=3-2 spectra. This crude technique provided the ionization balance of 40% F-like and 20% Ne-like in the case of 750 Å Se-1500 Å Formvar foil irradiated at $I=4 \times 10^{13} \text{ W/cm}^2/\text{beam}$ with $0.53 \text{ }\mu\text{m}$ light at a pulse length of 450 psec FWHM. Our significant omission was neglecting the process of F-like ion dielectronic recombination wherein we produce a doubly-excited Ne-like ion (with electrons in 3s or higher orbitals) which can then radiatively decay (it can also autoionize) in such a manner as to leave singly-excited states. This particular mechanism strongly favors population (by a factor of 5x) of higher degeneracy J=2 levels of the n=3p orbital. In addition, the 3s levels also get populated by the same mechanism leading to an actual lowering of the gain on the J=0 to 1 transition while actually boosting it on the J=2 to 1 lines. It is important to note that even though our simple initial modeling got the ground-state ionization balance presumably correct, we did not predict the channel that accounts for significant laser gain, namely the excited state ionization balance which is fed by this dielectronic recombination plus radiative cascade mechanism.

As a fix for our previous omission, we now include doubly-excited states which are fed by dielectronic recombination in all our atomic data files which are input into our laser simulation code XRASER along with 2D hydrodynamic calculations from the LASNEX laser-plasma interaction code. In Fig. 2a and b we compare our new and old calculated results for gain vs time for the J=0 to 1 and one of the J=2 to 1 lines. The results come from one of the central geometric zones of the gain region and represent a typical performance. As earlier estimated we see that the general difference between the old and the new is a net decrease in the gain of J=0 to 1 line and an increase of the J=2 to 1. Insofar as the time behavior, the 0 to 1 line achieves a higher gain than the 2 to 1 early in time when refraction effects² are bad owing to steep density gradients off the surface of an, as yet, unexploded foil. Much later times are irrelevant because the electron density has dropped markedly, dragging

the gain down with it. The time of most interest for comparing the two lines is the interval of roughly 0-200 psec after the peak of the driving laser pulse. It is within this interval that we believe the conditions are optimum for gain in this amplifier, namely density gradients are minimum thus minimizing the effects of refraction on x-ray laser propagation but density is still large enough so that the gain still remains high. During this optimum time interval the predicted gain (including line trapping) on the 182.4 Å J=0 to 1 line is about 5 cm^{-1} whereas the gain on the J=2 to 1 line at 209.6 Å is about 6 cm^{-1} (the other J=2 to 1 line at 206.3 Å has a similar gain). Although we now have seen all the lines from Fig. 1, the J=0 number is still too high compared to experiment. There is still no complete explanation for this discrepancy. However, there is now closer agreement between theory and experiment on the absolute value of gain for the J=2 lines.

In dealing with exceptionally long amplification lengths the refraction problem arises. One of our important goals for the Se amplifier has been to demonstrate amplifier saturation so that we can determine the overall efficiency of the x ray laser amplifier. As a result the Nova 2 beam laser facility was outfitted with opposed beam cylindrical optics which can achieve lengths to 52 mm per beam. This would allow us to achieve 25 gain lengths for J=2 to 1 transitions which is sufficient to achieve saturation. However, as is shown in Fig. 3, with the present amplifier design we predict severe refraction effects when we attempt to propagate beyond 2 cm. In addition, for lengths greater than 3 cm no laser trajectories can propagate through the center of the amplifier. This means that for a 3 cm target one might expect to collect considerably more signal in beamlets 10-20 mrad off the pointing axis of the amplifier. This is quantitatively illustrated in the figure since very few rays are present on axis and many are bunched off axis. We will show experimental evidence for this effect later in this manuscript. We are working on cures for the propagation problem. In general, the propagation distance goes linearly with the transverse density gradient for a fixed electron density and xray laser wavelength. This means we must design even better exploding foil amplifiers which have density scale lengths 2 to 3 x longer than the present values of 100-200 μm .

One last area receiving considerable theoretical effort is the design of x ray lasers to achieve amplification at less than 44 Å in a single-mode and at multi-MW power levels. Methods to achieve single-mode (fully coherent beams) at high power levels will be discussed in later papers.⁵ Our present designs for shorter wavelength schemes are as follows: In the near term we think we can push the Ne-like scheme to as short as 80 Å (one of the J=0 to 1 lines) in the case of Z=47 or Ag. Indeed we have already achieved lasing in Ne-like Mo down to wavelengths as short as 106 Å. Spectra illustrating this will be shown later in this manuscript. In the longer term Ne-like schemes do not exhibit a fast enough scaling in wavelength as a function of Z. The pump laser power required to reach saturation scales⁶ as λ^{-4} .

Ni-like analogs to the Ne-like schemes are an alternate method to achieve inversion at x-ray wavelengths. In this case you attempt to achieve a population inversion between the 4f,d and 4d,p levels. Shorter wavelengths than with Ne-like occur for the same amount of laser power invested because the levels are separated by larger amounts. A near term scheme of interest is Ni-like Gd(Z=63) which for nearly the same irradiance conditions as Se achieves gains at wavelengths down to 80 Å. In the longer term with higher power we could achieve sub 40 Å by pumping Ni-like Pb.

Experiments are also planned to study three-body recombination pumped schemes such as H-like Al. Although we predict relatively low gains of $1-2 \text{ cm}^{-1}$ for n=4 to 3 schemes, they may be ideal for use with multilayer mirrors operated at normal incidence in order to achieve multipass amplification. If we can amplify the H-like Al H α line we can clearly achieve the goal of short wavelength. Many other schemes to achieve efficient lasing at shorter wavelengths are also being considered and will be reported if progress warrants.

Experiments

Since the Novette experiments we have concentrated our experimental effort in three critical areas: 1) building and activating the Nova 2-beam laser facility; 2) constructing improved x ray laser diagnostics; and 3) planning and executing experiments to achieve saturated output with the Se amplifier, attain lasing at wavelengths less than 100 Å, increase our physics understanding of x ray amplification, and demonstrate some noteworthy applications of the laser.

The Nova 2-beam laser facility has been especially designed to perform x ray laser experiments. Especially important for x ray laser studies are the variable line length cylindrical lenses. We can continuously change the focus from 100 μm diameter circular (best focus) to 100 μm by 5.2 cm cylindrical. This allows us to pump power intensive schemes with a short line focus without wasting laser energy by overfilling the target or, conversely, to pump very long targets which require low laser power. Another important feature of the new facilities that we have a separate but synchronized timing laser (whose pulsewidth is ~ 30 psec FWHM) for triggering our diagnostics whose pulsewidth is independent of that of the main laser. Finally, we are able to produce at least a factor of 2x more power than with Novette and we have the capability to operate with either second or third harmonics of the 1.053 μm wavelength fundamental.

A NFD or near field diagnostic (formally, speaking neither the near or far field) is a new addition to our diagnostics which provides a measure of the x ray laser beam pattern: at 160 cm from the source or, if equipped with an x ray diode instead of film, it can give absolute x ray energy values for the x ray laser. As currently operated it can produce pattern images that represent about 50 mrad of horizontal divergence and 15 mrad vertical. With a carbon mirror operated at $2\theta = 11^\circ$ and an Al filter its sensitivity is peaked at a wavelength which coincides with the Se x ray laser or about 200 Å.

The status of x ray laser measurements at the time of this conference are shown in Fig. 4. We have now observed some $1.4 \times$ ray transitions which are amplified using the Ne-like $n=3p-3s$ inversion scheme and the exploding foil amplifier. Figure 4a, b, and c shows representative spectra from Ne-like Se (2.5 cm amplifier length), Y (2.9 cm amplifier length) and Mo (1.5 cm amplifier), respectively. In the spectrum of Se we have deliberately allowed the brightest $J=2-1$ lines to saturate the detector in order to show some of the other weaker lasing transitions that were originally predicted in Fig. 1. The $182.42 \text{ \AA}$ $J=0$ to 1 line is now clearly seen although much weaker than the $J=2$ to 1 . When the $J=2$ lines are attenuated to lie within the sensitivity range of McPigs the $J=0-1$ line cannot even be seen. From this observation as well as intensity vs amplifier length measurements we estimate its gain to be at most $1-2 \text{ cm}^{-1}$, much less than predicted. In the Y spectrum we are only able to see four of the five lines shown in the Se data. The $J=0-1$ line is predicted to occur at $154 \text{ \AA}$ while the lower $J=2-1$ line is predicted to occur at $155 \text{ \AA}$. Since the observed line at 155 is much stronger than the other $J=2$ (not the case in either Se or Mo) we can speculate it could actually be a blend of both $J=0$, $2-1$ lines. Only higher resolution measurements or larger amplification length targets will enable us to sort out this curious spectrum. Production of amplification in Y requires twice the pump laser power as for Se as well as a target of thickness $850 \text{ \AA}$ Y on the same thickness of Formvar. The gain on the Y $J=2-1$ lines has not yet been determined but we estimate to be at least $4-5 \text{ cm}^{-1}$.

Our best experimental achievement to date has been the demonstration of amplification in a Ne-like Mo exploding foil amplifier. The target thickness here was about $1200 \text{ \AA}$ Mo on Formvar and the Nova laser was operated at $4 \times$ the power required for Se. This high power requirement restricted our total amplification lengths to 1.5 cm maximum and necessitated use of best vertical focus ($100 \text{ }\mu\text{m}$ instead of $300 \text{ }\mu\text{m}$ normally used with Se). Nevertheless, this marks a significant extrapolation Ne-like scheme toward higher Z . In addition to the strong amplification of the normal $J=2-1$ lines two other interesting features appear in this data. First, the normal $J=0-1$ line ($182 \text{ \AA}$ equivalent in Se) has now shifted to longer wavelengths than the big $J=2-1$ lines. This occurs because of the different scaling with Z of spin-orbit effects on level binding energies. In our case it is ironically fortunate that the predicted biggest transitions is observed to be not only very weak but to have an unfavorable Z scaling. Second, notice a bright transition occurring at $106 \text{ \AA}$. This is the other $J=0-1$ line which was predicted to have small gains in Se at $169 \text{ \AA}$. As Z increases it is predicted to have higher gain (comparable to the $J=2-1$ and other $J=0-1$). Finally, it is important to mention that if we make Ne-like Ag lase this shorter wavelength $J=0-1$ line will occur at $80 \text{ \AA}$ and is predicted to have gain comparable to the $J=2-1$ which would occur at $99 \text{ \AA}$.

We are presently deriving gain curves for all the Mo lines. Current estimates put the $J=2-1$ lines at $3-4 \text{ cm}^{-1}$ which is in fairly close agreement with theory. One reason for this weak scaling of gain with Z is that we have increased the electron density (hence, the ion density) about $2 \times$ in the amplifier region as compared to the Se case.

The output power measured to date is at least 1 MW at 206 and 209 Å. This corresponds to about 200-250 μ J being radiated in one direction by the x ray laser lines. This number is fairly uncertain at the moment since we have not absolutely calibrated the instruments used to derive it. It is, however, about a factor of 10 x lower than was anticipated at amplifier saturation ($g_l=25$) which should have occurred at 5 cm of amplifier lengths. The values quoted were for 4.4 cm of length. Furthermore, beam pattern pictures taken with the NFD instrument illustrate that the beam is breaking into two segments, a strong lobe which has a geometric horizontal divergence of about 8 mrad and a vertical divergence of about 17-18 mrad, and a weak lobe of similar divergence, whose relative intensity increases with amplifier length. Both these lobes are separated from the original pointing direction by about 10 mrad, a separation which does not vary with amplifier length from 3 to 4 cm. Figure 5a and b shows the beam pattern photo and an intensity plot obtained by scanning the photo along its horizontal midplane. This refracted beam pattern is remarkably similar to that which was earlier predicted.

In conclusion, we assert that the demonstration of x ray lasers at Livermore is proceeding at a healthy pace toward ever shorter wavelengths and more power. However, the beam quality is poor owing to refraction effects in the exploding foil amplifier. Amplifier designs to cure the refraction are possible and are being pursued. Although the accuracy of predicting laser gain performance is improving we still do not know why J=0-1 monopole excitation lines are so weakly amplified.

The future focus of our program is to produce high coherent power at wavelengths shorter than 44 Å. We have outlined numerous schemes to achieve this but enormous pump laser power will be required unless we can make efficient multipass amplifiers which utilize semitransparent multilayer mirrors. Experiments to assess those possibilities are being planned.

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References

1. D. L. Matthews, et al., Phys. Rev. Lett. 54, 110 (1985).
2. M. D. Rosen, et al., Phys. Rev. Lett. 54, 106 (1985).
3. A. Zherikhin, K. Koshelev, and V. Letokhov, Sov. J. Quant. Mech. 6, 82 (1976).
4. A. V. Vinogradov and V. Shlyaptsev, Kvatn. Elektron. (Moscow) 10, 2325 (1983) [Sov. J. Quantum Electron, 13, 1511(1983)].
5. M. D. Rosen, J. Trebes, D. Matthews, submitted to Comments in Plasma Physics.
6. M. D. Rosen, P. L. Hagelstein, and R. A. London, in preparation.
7. B. MacGowan, private communication.

Fig. 1. Ne-like-Se $3p-3s$ lasing transitions (jj coupling notation) with predicted gains, α , in cm^{-1} .

Fig. 2. a) Gain vs time for $J = 0$ to 1 transition. New model has self-consistent dielectronic recombination. b) Same as a) for $J = 2$ to 1 transition.

Fig. 3. X-ray laser beam trajectories refracting as they proceed down a 3 cm length.

Fig. 4. a) 3p-3s lasing lines of Ne-like Se; b) Same as a) for Y; c) Same as a) for Mo.

Fig. 5. a) Photo of beam pattern; b) Line-out of a).