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Demonstration of a narrow-divergence x-ray laser in neonlike titanium

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We report an observation of soft-x-ray lasing in Ti, at 326.5 Å, based on recent experiments conducted on the Glass Development Laser (1.054 μm) at the Laboratory for Laser Energetics and the Nova laser (0.53 μm) at Lawrence Livermore National Laboratory. This Ti laser, which has been identified as a $3p \rightarrow 3s$ transition in Ne-like Ti, is unusual in several ways; the $J=0 \rightarrow 1$, $3p \rightarrow 3s$ transition is observed to be the dominant laser line in a Ne-like spectrum, the laser output has a very narrow divergence, and lasing is observed only in experiments where the main optical pulse is preceded by a low-intensity prepulse. We describe the experimental results and present evidence that suggests the gain is enhanced by resonant photopumping of the Ne-like Ti $2p \rightarrow 4d$ transitions by $3s \rightarrow 2p$ C-like and $3d \rightarrow 2p$ N-like Ti lines, which results in lasing on the $3p \rightarrow 3s$ transitions in Ne-like Ti.

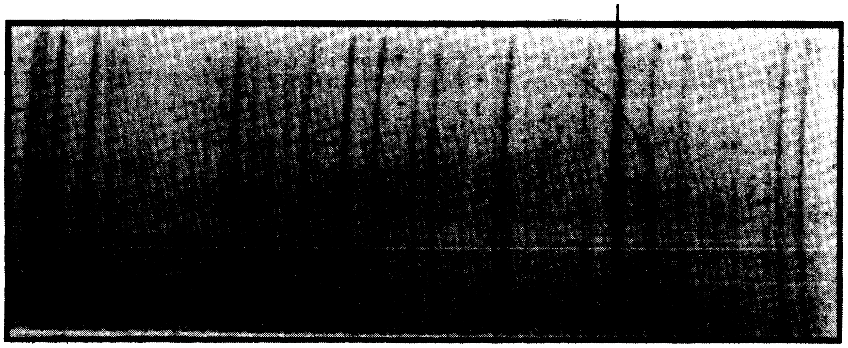
Since the first demonstration[1,2] of soft-x-ray lasing using the collisional excitation mechanism in Ne-like Se, several other Ne-like ions ranging[3-6] from Cu ($Z=29$) to Mo ($Z=42$) have been made to lase. This Rapid Communication presents the demonstration of lasing in a Ne-like ion with much narrower divergence compared with other Ne-like lasers and is the first Ne-like laser where the $J=0 \rightarrow 1$, $3p \rightarrow 3s$ transition is the dominant lasing transition. Based on the experimental results described in this Communication, we speculate that the gain is enhanced by resonant photopumping. While resonant photopumping was one of the early methods proposed for x-ray lasers,[7,8] to date it has not been observed and the shortest wavelength at which significant gain has been measured using resonant photopumping is at 2163 Å in Be-like C.[9]

Experiments were conducted initially at the Laboratory for Laser Energetics (LLE) at the University of Rochester on the Glass Development Laser (GDL) using $\lambda=1.054$ μm, and then at Lawrence Livermore National Laboratory (LLNL) on the Nova laser using $\lambda=0.53$ μm. We describe the instruments and experimental geometries used at both laboratories. We then present the experiments on GDL, which first demonstrated lasing on the Ne-like Ti transition at 326.5 Å, and the Nova results, which further confirmed lasing. Finally we discuss the resonant photopumping mechanism which may enhance the gain of this laser.

In the GDL experiments, 125-μm-thick Ti slabs were irradiated on one side by the GDL laser (1.054 μm). The basic geometry is described in Ref. 10. The optical laser had a 650-ps full width at half maximum (FWHM) Gaussian pulse with 200 J of energy which was focused to a 80-μm-wide (FWHM) by 2.2-cm-long focal line, resulting in a peak intensity of 1.7×10^{13} W/cm^2. In addition, a prepulse (also 650-ps FWHM) with 0.5% of the main pulse energy preceded the main pulse by 7 ns. In the Nova experiments, two beams of the Nova II laser illuminated simultaneously each side of a 125-μm-thick 3.8-cm-long Ti slab. The experimental configuration is similar to that described in Ref. 11. The thickness of the Ti slab allows each side of the target to behave independently, in effect creating two separate plasmas simultaneously. Each beam of the Nova laser had a 600-ps FWHM Gaussian pulse with 550 J of energy which was focused to a 120-μm-wide (FWHM) by 5.4-cm-long focal line. The resulting peak intensity was similar to that of the GDL experiments. The Nova experiments differed from the GDL experiments in the wavelength of the optical laser, 0.53 vs 1.054 μm, the use of time-resolved diagnostics, a longer Ti target, and the fact that the optical prepulse similar to that present on GDL could be turned on or off for different shots.

At GDL, the principal instrument was a 1-m grazing-incidence grating spectrograph (GIGS) which was used to view the plasma end-on and to detect the output of the x-ray laser. The GIGS spectrograph has an acceptance angle of 20 mrad in the direction along the entrance slit and 1 mrad perpendicular to the slit with the entrance slit oriented perpendicular to the target surface. It records time-integrated x-ray spectra between 15 and 350 Å on Kodak 101 film. At Nova, the principal instruments were a time-gated, microchannel-plate intensified grazing-incidence grating spectrograph (MCPIGS) and a streaked flat-field spectrograph (SFFS); both of these instruments observed the axial output of the x-ray laser. The MCPIGS provided angular coverage over ±4.7 mrad about the x-ray laser axis, while the SFFS looked at only one surface of the foil with an angular acceptance of 0–10 mrad with respect to that surface. The angular resolution of both instruments was perpendicular to the target surface.

The GDL experiments showed Ti lasing at 326.5 Å, resulting in a very directional output (4-mrad FWHM) in the direction perpendicular to the target surface. The x-



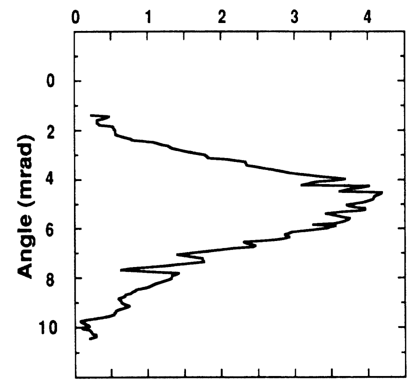


FIG. 1. Photograph of the on-axis spectrograph film in the region of 300–340 Å obtained in the GDL experiments with the GIGS spectrograph from a 2.2-cm-long Ti target. A spectral analysis indicates that the lasing line at 326.5 Å is far brighter than any other line in the spectrum. The plot of the intensity of the 326.5-Å line vs angle shows the narrow angular extent of the x-ray laser output. By comparison, the nonlasing lines uniformly fill the spectrograph.

ray laser beam is deflected by 5 mrad toward the pump laser, away from the target surface. Figure 1 is a photograph of the on-axis spectrograph film in the region of 300–340 Å. A spectral analysis indicates that the line at 326.5 Å is far brighter than any other line in the spectrum.[12] The angular distribution shows the narrow divergence of the x-ray laser output as compared with the nonlasing lines which uniformly fill the spectrograph. By comparison, previous measurements[13,14] of the angular distribution of Ge and Se lasers show 8–20-mrad FWHM divergence in the direction perpendicular to the target surface. This spectral brightness and the narrow divergence of the beam are clear indications of lasing.

Because the angular output distribution of the x-ray laser is narrower than the acceptance angle of the spectrograph (along the slit) the laser beam irradiates only a narrow portion of the spectrograph film. This allows the spectrograph to observe the x-ray laser signal as well as the off-axis emission (≈ 10 mrad off the peak); from these measurements we estimate the time-integrated gain of the Ti laser (326.5 Å) to be 2–3 cm^{-1}. This value most likely serves as a lower bound to the actual gain since we cannot be sure what contribution refraction makes to the off-axis intensity at such small angles (<20 mrad).

Wavelength calibrations were performed at both LLE and LLNL and indicated that the measured laser wavelength was 326.5 ± 0.3 Å. Identification of the 326.5-Å line as being the $\overline{2p}_{1/2}3p_{1/2}(J=0) \rightarrow \overline{2p}_{1/2}3s_{1/2}(J=1)$ line is based on beam-foil experiments[15] which give a value of 326.3 ± 0.4 Å. The bar over the $2p$ state indicates a vacancy in the closed L shell $[1s^2 2s^2 2p^6]$. Our estimate of the line position, 326.2 ± 0.1 Å, uses an empirical correction factor determined by comparing the existing experimental data for nearby elements with the theoretical values calculated from the atomic physics code of Grant *et al.*[16] Extensive searches failed to identify any other candidate laser lines in Ti which could be at 326.5 Å.

Unlike the GIGS spectrograph used on the GDL experiments the spectral range of the MCPIGS and SFFS allowed us to observe the wavelengths where the other Ne-like Ti laser ($J=2,1,0 \rightarrow 1$) lines exist (414–509 Å).[15,17] A spectrum from the MCPIGS, Fig. 2, shows quite clearly the strong 326.5-Å laser line and the weaker $J=1 \rightarrow 1$ and $J=0 \rightarrow 1$ transitions at 473.2 ± 0.5 Å and 508.8 ± 0.5 Å which may also be lasing. The analog to the strong $J=2 \rightarrow 1$ Ne-like Se laser lines at 206 and 209 Å which would be at 459.4 and 472.1 Å in Ne-like Ti were not observed to lase. Thus Ti clearly differs from other Ne-like lasers which have the $J=2 \rightarrow 1$ lines significantly brighter than the other lasing lines.

In Fig. 3 we plot the time history of the x-ray laser intensity from the SFFS for the 326.5-Å line with time zero corresponding to the peak of the optical laser pulse. The Ti lasing peaks at the peak of the Nova drive pulse to within the fiducial uncertainty of 30 ps and has a FWHM of 200 ps.

The optical laser intensity in these experiments was sufficiently high to ionize Ti well past the Ne-like stage. Indeed, emission lines of ions in the series from Ne- to He-like have been identified in the x-ray spectra[12] from these targets indicating that, as compared to the typical prescription for a Ne-like x-ray laser,[1–6] the Ti was greatly overionized. Subsequent experiments at lower irradiance, i.e., one that is considered optimal for lasing in Ne-like ions, failed to produce any lasing. The GDL experiments included at least ten shots each using similar slab targets made of adjacent elements, V ($Z=23$) and Sc ($Z=21$). No lasing was observed in the V or Sc, while Ti was observed to lase under similar conditions during this series of shots. This suggests that specific spectroscopic properties of Ti play a key role in this system.

In these experiments a variety of laser irradiation parameters were investigated. Lasing was never observed when single pulse irradiation was used; this included 600-ps Gaussian (1.054 and 0.53 μm), and 1- and 2-ns square (0.53 μm) pulses. Instead the 326.5-Å line is only seen to lase when the main heating pulse is preceded by a prepulse. Experiments which used a prepulse of 0.5% of

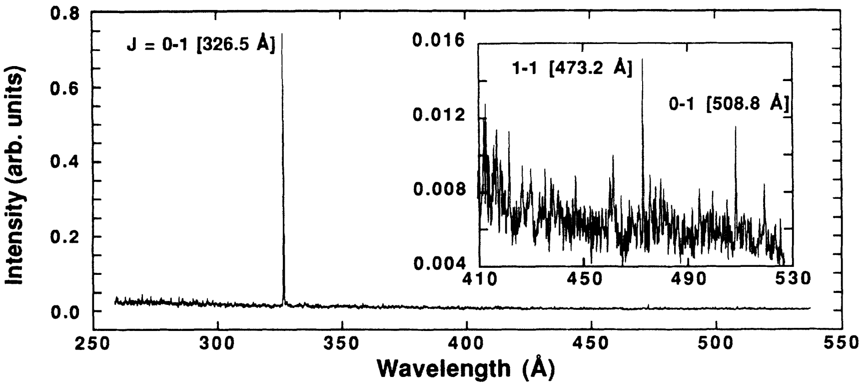


FIG. 2. Intensity vs wavelength obtained in the Nova experiments with the MCPIGS spectrograph from a 3.8-cm Ti target. The laser line at 326.5 Å dominates the spectrum. Two weaker lines are seen at 473.2 and 508.8 Å. Note the absence of the $J=2\rightarrow 1$ lines which would be expected at 459.4 and 472.1 Å.

the main pulse intensity 7 ns before the main pulse produced lasing with a reproducibility of 60%. Experiments with a prepulse 10 ns before the main pulse with intensities from 0.2%–20% of the main pulse failed to produce lasing.

Both the anomalous behavior of Ti compared with known Ne-like lasers and the absence of lasing in neighboring Z's suggest that the lasing is enhanced by resonant photopumping of the Ne-like Ti by strong emission lines from C and N-like Ti. This mechanism would also explain the requirement for overionizing the Ti. Figure 4 shows the proposed photopumping mechanism which depicts C-like $3s\rightarrow 2p$ and N-like $3d\rightarrow 2p$ lines resonantly photopumping electrons in the ground state of the Ne-like Ti ion to the $\overline{2p}_{3/2}4d_{5/2}(J=1)$ and $\overline{2p}_{1/2}4d_{3/2}(J=1)$ levels. The $\overline{2p}_{3/2}4d_{5/2}(J=1)$ and $\overline{2p}_{1/2}4d_{3/2}(J=1)$ levels decay strongly to the $\overline{2p}_{1/2}3p_{1/2}(J=0)$ level, which is the upper laser state. This upper laser level lases at 326.5 Å to the $\overline{2p}_{1/2}3s_{1/2}(J=1)$ level which then decays rapidly to the Ne-like ground state. Other levels are also fed by the decay of the $4d$ levels and can result in additional laser lines[15,17] as shown in Fig. 4.

The wavelength of the C-like Ti $2s^22p3s\,^3P_2\rightarrow 2s^22p^2\,^3P_1^o$ pump line has been measured[18] to be at 19.369 ± 0.010 Å and the N-like Ti $2s^22p^2(^1D)3d\,^2F_{7/2}\rightarrow 2s^22p^3\,^2D_{5/2}^o$ and $2s^22p^2(^3P)3d\,^2D_{5/2}\rightarrow 2s^22p^3\,^2D_{5/2}^o$ lines have been measured[19] to be at 19.210 ± 0.005 Å and 19.370 ± 0.005 Å, respectively. The ground state to the $\overline{2p}_{3/2}4d_{5/2}(J=1)$ transition in Ne-like Ti has been measured to be at 19.366 ± 0.005 Å while the ground state to the $\overline{2p}_{1/2}4d_{3/2}(J=1)$ transition has been measured to be at 19.204 ± 0.005 Å.[20] The resonances between the lines vary from 3–6 mÅ. The Doppler width for the 19-Å Ti lines in a plasma with an ion temperature of 100 eV is 2.1 mÅ. The actual linewidth for optically thick pump lines will be greater due to opacity broadening and bulk Doppler shifts. Line-transfer calculations done at LLNL using XRASER (Ref. 21) predict linewidths greater than 10 mÅ, consistent with linewidths measured at shorter wavelength. For the NaX He-α line at 11 Å, an opacity

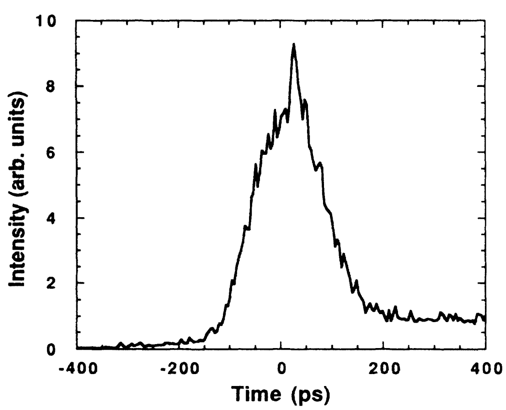


FIG. 3. The x-ray laser intensity for the 326.5-Å line vs time with time zero corresponding to the peak of the Nova optical laser pulse.

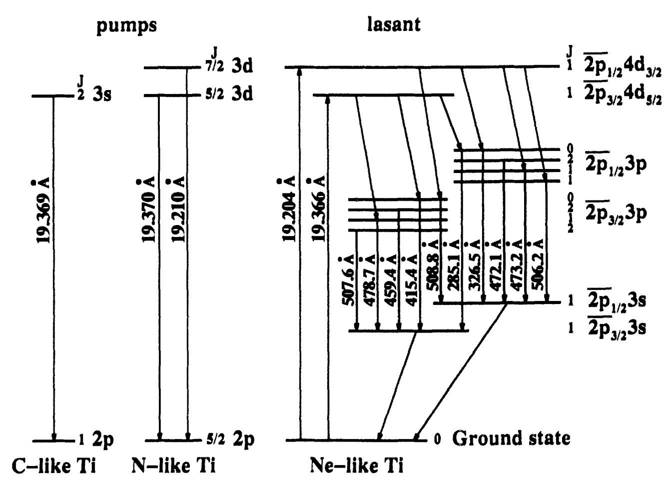


FIG. 4. The energy-level diagram shows the proposed resonant photopumping mechanism. The C-like $3s\rightarrow 2p$ line and the N-like $3d\rightarrow 2p$ lines pump the two Ne-like Ti $2p\rightarrow 4d$ transitions which results in gain on the $3p\rightarrow 3s$ laser lines. A detailed specification of the configurations for the C and N-like lines is given in the text. References 15 and 17 specify the detailed configurations for the laser lines.

broadened linewidth, with an upper bound of 35 mÅ, has been measured[22] while a 14-mÅ linewidth has been observed for the Al XIII Ly-β line at 6 Å.[23] Therefore it is reasonable to believe that adequate overlaps occur for resonant photopumping.

LASNEX one-dimensional (1D) computer simulations[24] suggest that the prepulse may affect lasing in two ways: via refraction and plasma kinetics. Slab targets have been found to produce density gradients which are steeper than exploding foil targets and are therefore limited in their effective lasing length by refraction.[25] Our computer simulation results for slab targets, with and without a prepulse, indicate that a prepulse helps create a less steep density gradient than without the prepulse. This allows the lasing x-rays to traverse more of the gain medium before being refracted out of the plasma and therefore is compatible with the narrow divergence observed. In regard to laser kinetics, these simulations indicate that, at the time of peak x-ray lasing, the prepulse produces a steep gradient in the electron temperature where the hot plasma (main pulse) encounters the cooler plasma (prepulse). This results in a lower electron temperature in the lasing region, thereby producing a higher Ne-like fraction than the case without a prepulse. It also enables a colder region of Ne-like ions to be spatially near a hot region of C- and N-like ions thereby enhancing the x-ray coupling for photopumping. These preliminary findings point to the manner in which the prepulse affects the performance of this laser but require further study.

In conclusion, we have observed a Ne-like Ti laser at 326.5 Å which has unusually narrow divergence and requires a prepulse in order to lase. These experiments suggest that Ti is unique and that gain may be enhanced by resonant photopumping of the Ne-like transitions by C- and N-like lines. If this explanation can be verified in future experiments it would represent the first demonstration of a resonantly photopumped soft x-ray laser.

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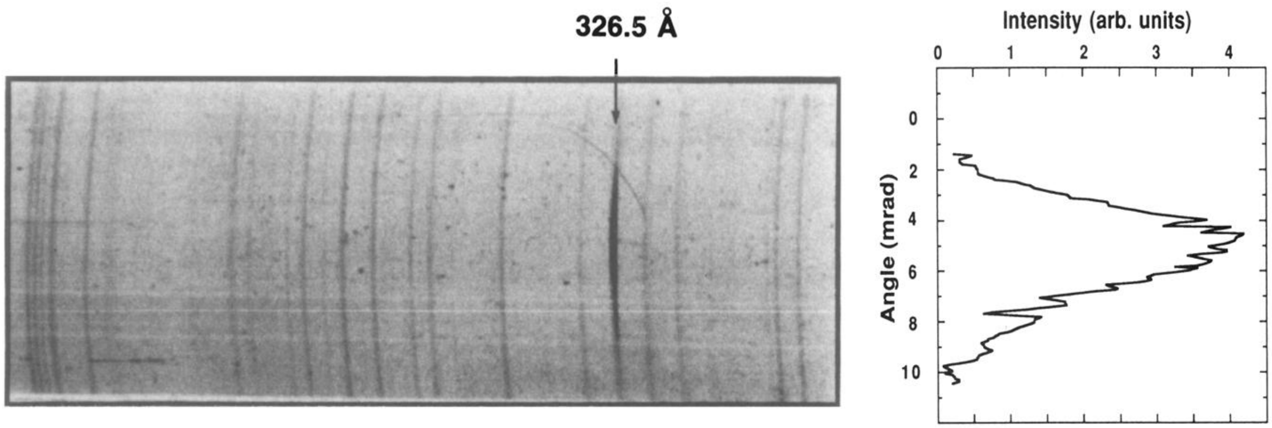

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