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First Observation of Lasing at 231 Å in Neon-Like Nickel Using the Prepulse Technique

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Abstract. We report lasing for the first time in nickel on the neon-like $J = 0 \to 1$, $3p \to 3s$ transition at 231 Å as well as several weaker transitions including the $J = 2 \to 1$ lines at 298 Å and 304 Å. Amplification is seen only when the prepulse technique of using a low intensity prepulse before the main optical drive pulse is used to illuminate the nickel target. The prepulse technique is also shown to produce lasing in copper and dramatically improve the output of the germanium laser.

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Recently, lasing has been demonstrated in low-Z neon-like ions [1, 2] of titanium ($Z = 22$), chromium ($Z = 24$), and iron ($Z = 26$) by applying the prepulse technique of using a low intensity prepulse before the main optical drive pulse to illuminate the laser target. This paper presents evidence for lasing in neon-like nickel ($Z = 28$), copper ($Z = 29$), and germanium ($Z = 32$) using this new technique which helps to preform the plasma amplifier. The $J = 0 \to 1$, $3p \to 3s$ transition, which is at 231, 221, and 196 Å in nickel, copper, and germanium, respectively, dominates the spectra as it also did for titanium, chromium, and iron, and as was originally predicted [3, 4] many years ago but never observed in higher-Z elements such as selenium. We also report lasing on other $J = 2 \to 1$ and $J = 1 \to 1$ transitions of nickel, copper, and germanium and show that the time history of the strongest $J = 2 \to 1$ line is much different than the $J = 0 \to 1$ laser line.

Experiments were conducted at Lawrence Livermore National Laboratory (LLNL) using two beams of the Nova laser at $\lambda = 0.53$ µm. In a typical experiment, the Nova laser illuminated both sides of a 125 µm thick, 4.5 cm long nickel slab which had 4000 Å of germanium coated on one side. The above length of the target was reduced by a 16% gap in the center which results in an actual length of 3.8 cm. Each Nova beam was a 600 ps FWHM Gaussian pulse with 1100 J of energy in a 120 µm wide (FWHM) by 5.4 cm long line focus, resulting in a peak intensity of 34 TW/cm^2. A 6 J prepulse (also 600 ps, FWHM) preceded the main pulse by 7 ns. All experiments discussed in this paper used these nominal conditions, except where noted.

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 resolution over 10 mrad near the X-ray laser axis, while the SFFS integrated over an angular acceptance of 10 mrad. The angular resolution of both instruments was perpendicular to the target surface. The MCPIGS used a 600 line per mm grating and had spectral coverage of approximately 150 Å to 680 Å. Lasing was determined by observing the high spectral brightness of the lasing lines relative to the strong emission lines on-axis and the short time duration of the lasing relative to the optical drive pulse.

With the MCPIGS aligned on the laser axis, we could observe both sides of the germanium-coated nickel slab lase as though they were separate experiments. The angular resolution of the MCPIGS allows one to observe the two materials lase and see each laser refract towards the Nova beam which illuminated that material. Fortunately, each laser peaks approximately 5 mrad off-axis, so the peak lasing from each material can be observed on opposite edges of the MCPIGS angular coverage. Other experiments done on germanium, which looked from on-axis to 10 mrad off-axis, have observed the germanium laser to peak 5 mrad off-axis. Figure 1 shows spectra of nickel and germanium from the MCPIGS taken on a single shot using the prepulse technique with each material observed 4–5 mrad off-axis toward the Nova beam which illuminated that side. The strong neon-like germanium $J = 0 \to 1$ laser line at 196.06 Å dominates the $J = 2 \to 1$ laser lines at 232.24 Å and 236.26 Å. The two weaker lines at 247.32 Å and 286.46 Å are also observed and these five laser lines [5] are used as reference lines to calibrate the nickel spectra. For the nickel spectrum shown in Fig. 1, the strong $J = 0 \to 1$ laser line at 231.1 Å completely dominates the weaker $J = 2 \to 1$ laser line at 303.6 Å as well as all the germanium laser lines shown in the figure.

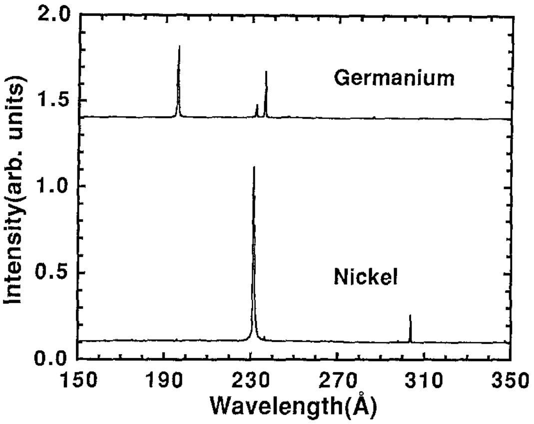

Fig. 1. MCPIGS on-axis spectra from each side of a 3.8 cm long germanium-coated nickel slab target illuminated with the Nova laser using the prepulse technique. For germanium, the neon-like $J = 0 \rightarrow 1$ laser line at 196 Å dominates the spectrum with the two $J = 2 \rightarrow 1$ lines at 232 Å and 236 Å quite visible. For nickel, the neon-like $J = 0 \rightarrow 1$ laser line at 231 Å dominates the spectrum with the $J = 2 \rightarrow 1$ line at 304 Å quite visible

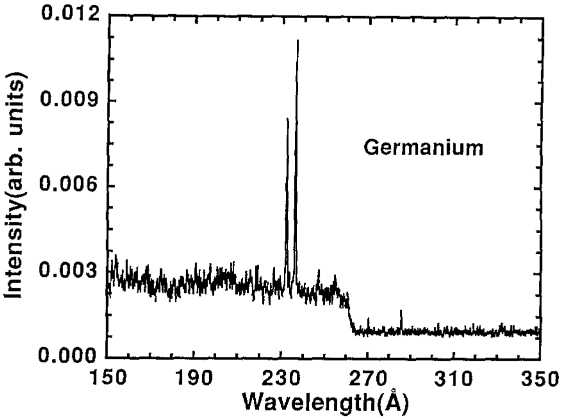

Fig. 2. MCPIGS on-axis spectrum from the germanium side of a 3.8 cm long germanium-coated nickel slab target illuminated with the Nova laser without using a prepulse. The neon-like germanium $J = 2 \rightarrow 1$ lines at 232 Å and 236 Å dominate the spectrum but are very weak compared with those in Fig. 1. The $J = 0 \rightarrow 1$ laser line at 196 Å is not seen

Identification of the 231.1 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 solar flare data and extrapolation of experimental data for lower-Z ions [6] which give values of 231.10 Å and 231.07 Å, respectively. (The bar over the $2p$ state indicates a vacancy in the closed L shell.) This line is the analogue of the 196.06 Å line in germanium. By comparing the existing experimental data for nearby elements with the theoretical values calculated from the multi-configuration Dirac-Fock (MCDF) atomic physics code of Grant [7] we estimate a value of 231.16 Å for this line, consistent with the experiments. The 303.6 Å line of nickel is the analogue to the familiar $J = 2 \rightarrow 1$ neon-like germanium laser line at 236.26 Å. The other $J = 2 \rightarrow 1$ line, the analogue to the 232.24 Å germanium line, is seen very weakly at 297.7 Å. These two lines are the $\overline{2p}_{1/2}3p_{3/2}(J = 2) \rightarrow \overline{2p}_{1/2}3s_{1/2}(J = 1)$ and $\overline{2p}_{3/2}3p_{3/2}(J = 2) \rightarrow \overline{2p}_{3/2}3s_{1/2}(J = 1)$ transitions, respectively, and they have been observed in beam foil experiments at 303.80 Å and 297.90 Å. We also observe very weak neon-like nickel lines at 347.5 Å and 314.8 Å which we identify as the $\overline{2p}_{3/2}3p_{1/2}(J = 2) \rightarrow \overline{2p}_{3/2}3s_{1/2}(J = 1)$ and $\overline{2p}_{3/2}3p_{3/2}(J = 1) \rightarrow \overline{2p}_{3/2}3s_{1/2}(J = 1)$ lines, respectively. The 347.5 Å line is the analogue of the very long wavelength $J = 2 \rightarrow 1$ line seen in many other neon-like ions; in germanium it is the analogue of the 286.46 Å line. The 314.8 Å line is the analogue of the $J = 1 \rightarrow 1$ line seen at 247.32 Å in germanium. These two lines are observed at 348.05 Å and 315.01 Å in the beam-foil experiments [6].

When the 3.8 cm long germanium-coated nickel slab was illuminated from each side with the nominal 1100 J Nova pulse but without the prepulse, the germanium was observed to lase weakly and no lasing was observed for the nickel. This is consistent with other nickel experiments done at Rochester where very weak emission was seen on the $J = 2 \rightarrow 1$ lines [8]. Figure 2 presents the peak of the germanium spectrum observed 4–5 mrad off-axis on the MCPIGS. The spectrum is dominated by the 232 Å and 236 Å lines and the $J = 0 \rightarrow 1$ line at 196 Å is not observed. Since previous experiments have observed a typical slab target of germanium to peak 13 mrad off-axis with a FWHM divergence of 10 mrad [9], the peak intensity of the germanium laser is likely occurring outside the field of view of the MCPIGS. However, comparing Figs. 1 and 2, which view the same angle and use the same intensity scale, the germanium laser using the prepulse is fifty times stronger than without the prepulse. The nickel laser is stronger yet.

When the 3.8 cm long germanium-coated nickel slab was illuminated from each side with a 550 J main pulse and a 3 J prepulse, as was used previously for titanium [1, 2], both materials lased but the germanium laser was observed very weakly on the MCPIGS and not at all on the SFFS while the nickel was observed as a strong laser on both instruments even though it was weaker in intensity, by a factor of 5–10, as compared with the nickel illuminated at nominal intensity. On the contrary, both nickel and germanium lased well when the nominal intensity of the main pulse is doubled as used for the copper experiments described below. Nickel appears to be a very robust laser which works over a wide range of conditions. We suspect that using the prepulse technique with a longer wavelength drive laser ($\lambda = 1.06\ \mu\text{m}$ or $1.3\ \mu\text{m}$) may further improve the efficiency of these lasers. With such a large parameter space of prepulse contrast and delay to explore, it is very likely that the efficiency of the nickel laser can still be significantly improved.

We also did one experiment with the prepulse technique on a 3.8 cm long copper slab using a 6 J prepulse followed 7 ns later by 2400 J in the main beam. The $J = 0 \rightarrow 1$ laser line at 221.1 Å was observed to dominate the spectra. The standard $J = 2 \rightarrow 1$ lines and several weaker $J = 2 \rightarrow 1$ and $J = 1 \rightarrow 1$ laser lines were also observed in copper. The wavelengths of the observed laser lines for nickel and copper are summarized in Table 1 along with uncertainties in the measured values. The longer wavelength lines have larger uncertainties because they are weak and are far from any calibration lines, especially the 331.5 Å copper line. The theoretical values have an uncertainty of 0.2 Å.

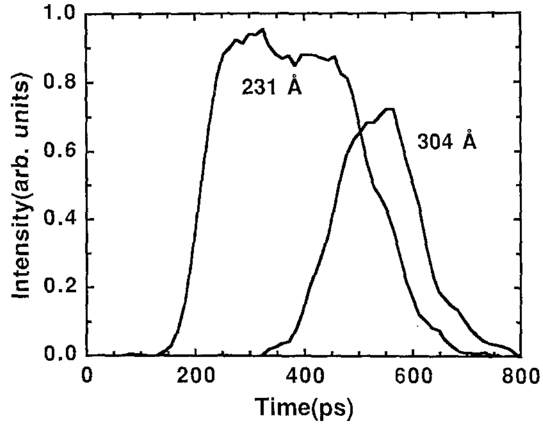

Fig. 3. Intensity of the neon-like nickel lines at 231 Å and 304 Å vs time as measured on the SFFS. The intensity of the $J = 2 \rightarrow 1$ line at 304 Å is multiplied by a factor of ten for comparison. The $J = 0 \rightarrow 1$ line at 231 Å lases approximately 200 ps before the 304 Å line

Table 1. Wavelengths of observed laser lines for neon-like nickel and copper

Ion	Lines observed	λ_{obs} [Å]	λ_{calc} [Å]
Ni XIX	$J = 0 \rightarrow 1$	231.1 ± 0.2	231.16
	$J = 2 \rightarrow 1$	297.7 ± 0.3	297.84
	$J = 2 \rightarrow 1$	303.6 ± 0.3	303.80
	$J = 1 \rightarrow 1$	314.8 ± 0.5	314.98
	$J = 2 \rightarrow 1$	347.5 ± 0.5	348.04
CuXX	$J = 0 \rightarrow 1$	221.1 ± 0.3	221.11
	$J = 2 \rightarrow 1$	279.3 ± 0.3	279.34
	$J = 2 \rightarrow 1$	284.7 ± 0.3	284.72
	$J = 1 \rightarrow 1$	296.2 ± 0.3	296.07
	$J = 1 \rightarrow 1$	331.5 ± 1.0	330.45

The time histories of the $J = 0 \rightarrow 1$ and $J = 2 \rightarrow 1$ lines are very different. Figure 3 shows the time history of the neon-like nickel lines at 231 Å and 304 Å using the prepulse technique. The intensity of the 304 Å line is multiplied by a factor of 10 in Fig. 3 in order to show the comparison. The $J = 0 \rightarrow 1$ line at 231 Å peaks approximately 200 ps before the $J = 2 \rightarrow 1$ line at 304 Å. The flat top on the 231 Å line is due to saturating the streak camera. The different time histories suggest that lasing is coming from very different regions in the plasma and that future measurements are needed with spatial and time resolution to better understand the plasma conditions and the processes which are driving each of these laser lines.

In conclusion, we have observed lasing in neon-like nickel which is dominated by the 231.1 Å $J = 0 \rightarrow 1$ laser line and which requires a prepulse in order to lase. When the same prepulse technique is used on germanium the normal spectrum is changed dramatically with the 196 Å $J = 0 \rightarrow 1$ line dominating the usual $J = 2 \rightarrow 1$ lines at 232 Å and 236 Å. Comparing the two neon-like laser systems, the essentially monochromatic nickel laser at 231 Å is brighter than the germanium laser and may be used in applications which now use the germanium laser, especially since the nickel laser is very near in wavelength to the germanium 232 Å and 236 Å lines which many experiments are designed for. Refraction is also observed to be significantly less when the prepulse technique is used for both of these lasers. This offers the potential for better multipass coupling needed to improve the laser efficiency and coherence. Additional calculations and experiments are needed to explore the full potential of the prepulse technique as applied to nickel and other materials.

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References

1. J. Nilsen, B.J. MacGowan, L.B. Da Silva, J.C. Moreno: Prepulse technique for producing low-Z Ne-like XUV lasers, University of California, Report UCRL-JC-112704, Livermore, CA (1993)
2. T. Boehly, M. Russotto, R.S. Craxton, R. Epstein, B. Yaakobi, L.B. Da Silva, J. Nilsen, E.A. Chandler, D.J. Fields, B.J. MacGowan, D.L. Matthews, J.H. Scofield, G. Shimkaveg: Phys. Rev. A **42**, 6962 (1990)
3. A.V. Vinogradov, I.I. Sobel'man, E.A. Yukov: Sov. J. Quantum Electron. **7**, 32 (1977)
4. R.C. Elton: *X-Ray Lasers* (Academic, San Diego 1990) pp. 99–126
5. E.A. MacLean, T.N. Lee, J.A. Stamper, C.K. Manka, H.R. Griem: J. Opt. Soc. Am. B **9**, 350 (1992)
6. J.P. Buchet, M.C. Buchet-Poulizac, A. Denis, J. Desesquelles, M. Druetta, S. Martin, J.F. Wyart: J. Phys. B **20**, 1709 (1987)
7. I.P. Grant, B.J. McKenzie, P.H. Norrington, D.F. Mayers, N.C. Pyper: Comput. Phys. Commun. **21**, 207 (1980)
8. T. Boehly, B. Yaakobi, D. Shvarts, D. Meyerhofer, P. Audebert, J. Wang, M. Russotto, B. Boswell, R. Epstein, R.S. Craxton, J.M. Soures: Appl. Phys. B **50**, 165 (1990)
9. T. Boehly, R.S. Craxton, R. Epstein, M. Rossotto, B. Yaakobi: Opt. Commun. **79**, 57 (1990)