Nearly Monochromatic Lasing at 182 Å in Neonlike Selenium

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The $J = 0 \rightarrow 1$, $3p \rightarrow 3s$ transition at 182 Å in neonlike selenium is observed to completely dominate the lasing output, as predicted but never observed before this work. Instead of a single long pulse we use a series of short 100 ps pulses from the Nova laser to illuminate slab targets of selenium. The 182 Å line is more than an order of magnitude brighter than the usual 206 and 209 Å laser lines. Similar behavior is observed for neonlike ions of germanium, zinc, and nickel.

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Since 1984 when the first x-ray lasing was demonstrated in Ne-like Se [1,2] at 206 and 209 Å one mystery has plagued our understanding of the collisionally driven Ne-like x-ray lasers. That is the question of why the $J = 2 \rightarrow 1$, $3p \rightarrow 3s$ transitions at 206 and 209 Å dominant the spectra while the $J = 0 \rightarrow 1$, $3p \rightarrow 3s$ transition at 182 Å which was predicted to be the dominant laser line has always been very weak and was not even observed in the early experiments [1–5]. In recent experiments using the prepulse technique the 182 Å line was seen much brighter than usual, but still the 206 and 209 Å lines dominated the output [6]. In this paper we use a multiple pulse technique to illuminate slab targets of Se, and we do see the 182 Å line as the brightest laser line by more than an order of magnitude. Similar behavior is observed for neonlike ions of germanium, zinc, and nickel where the 196, 212, and 231 Å lines dominate the spectra of the respective ions.

Experiments were conducted at Lawrence Livermore National Laboratory (LLNL) on the Nova laser using $\lambda = 0.53$ μm. One beam of the Nova laser illuminated the selenium coated (1 μm thick) side of a 125 μm thick, 3.0 cm long nickel slab which had a 0.48 cm gap in the middle resulting in an actual length of 2.52 cm. The Nova laser produced a series of 100 ps full width at half maximum (FWHM) Gaussian pulses which were 400 ps apart (peak to peak). Each pulse produced 400 J of energy in a 120 μm wide (FWHM) by 3.6 cm long line focus, resulting in a peak intensity of 110 TW/cm^2.

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 SFFS provided time resolution of 30 ps while the MCPIGS was time integrated for the duration of the three pulses. The MCPIGS used a 600 lines/mm grating and had spectral coverage of ≈150–680 Å.

Lasing was determined by observing the high spectral brightness of the lasing lines relative to the strong emission lines on axis, the angular collimation of the lasing lines, the short time duration of the lasing relative to the continuum emission, and the exponential growth of the laser output as the length was increased.

For the 3 cm long Se target illuminated with three pulses as described above, Fig. 1 shows a spectrum from the MCPIGS spectrograph. The Ne-like Se $J = 0 \rightarrow 1$ laser line at 182 Å dominates the weaker $J = 2 \rightarrow 1$ laser lines at 206 and 209 Å by factors of 20 and 37 for the time integrated data shown here. With the sensitivity of the time resolved SFFS spectrometer set to observe the weak 206 and 209 Å lines, the 182 Å line consistently saturated the detector, so a good quantitative comparison was not possible. However, we do observe the 182 Å line to peak approximately 50–80 ps earlier in time than the 206 and 209 Å lines. The 182 Å line is also observed to be an order of magnitude brighter in the time integrated data

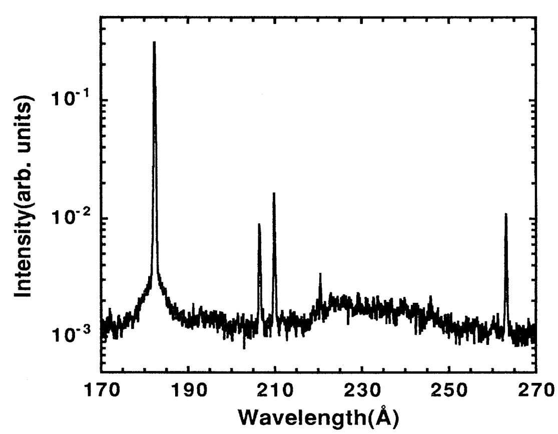

FIG. 1. MCPIGS on-axis spectrum obtained in the Nova experiments from 3 cm long targets of Se illuminated by a series of three 100 ps pulses 400 ps apart with peak intensity of 110 TW/cm^2. The Ne-like $J = 0 \rightarrow 1$ laser line at 182 Å dominates the spectrum. The $J = 2 \rightarrow 1$ lines at 206 and 209 Å as well as the other laser lines at 220 and 262 Å are quite visible.

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when compared with the earlier Se experiments which used a prepulse [6].

For Se we did not estimate the gain because of lack of data for different length targets. However, for Ge targets we did experiments at several lengths and measured a gain of 4.1 cm^{-1} for the $J = 0 \rightarrow 1$ line at 196 Å and 4.3 cm^{-1} for the $J = 2 \rightarrow 1$ line at 236 Å. The Ge 196 and 236 Å lines are analogs of the 182 and 209 Å Se lines. The Ge experiments were done using the same pulse shapes used for Se but with two-thirds the intensity and with a traveling wave geometry [7] to eliminate the transit time effect associated with propagation down the x-ray laser axis. The 196 Å line also saturated the detector, but we did observe the 232 and 236 Å lines to lase approximately 50 ps after the peak of the 196 Å line with a time duration of 60 ps. Recent experiments [8] done on the Gekko XII laser in Osaka using double pulse (100 ps) illumination of a curved Ge target has also seen the $J = 0 \rightarrow 1$ line at 196 Å dominate the Ge spectra and have measured a gain of 3.5 cm^{-1} for this Ge laser line.

Experiments were also done on Se targets using the same pulse shapes but with a lower intensity. When the peak intensity was decreased by one-third to 73 TW/cm^2 the Se did lase but was weaker by an order of magnitude on the 182 Å line which continued to dominate the spectral output. When the peak intensity was lowered even further to 50 TW/cm^2 the Se was not observed to lase.

Based on our calculations, we believe the multiple pulses are creating a larger, more uniform density plasma, at the densities required for lasing at these short wavelengths. The first pulse heats and expands the plasma. At this time the gradients in the electron density are too steep for any significant laser propagation and the gain region is very small. However, during the second and third pulses a much larger and more uniform plasma is created which can directly absorb the optical drive pulse and which is at the right densities for gain and laser propagation. To model these experiments we did LASNEX one-dimensional (1D) computer simulations [9] of the Se slab illuminated by three 100 ps pulses. The LASNEX calculations included an expansion angle of 15° in the dimension perpendicular to the primary expansion so as to simulate 2D effects. Figure 2 shows the electron density versus distance from the surface at the time of peak illumination by the three optical drive pulses labeled 1st, 2nd, and 3rd. Also shown by the dotted line is the electron density profile at the time of peak illumination for the case of a single 600 ps Gaussian pulse with peak intensity 70 TW/cm^2 illuminating a Se slab target. During the first pulse of the multiple pulse case the density falls off exponentially and is within 50 μm of the target surface. During the second pulse the density falls off exponentially near the target surface but then has a region of more gradual decrease starting about 60 μm from the surface. It is in the density range between 10^{20} and 10^{21} electrons/cm^3 that the gain exists. During the third pulse the gradients in the electron density becomes even smaller while the density itself increases in the region 100 to 200 μm from the surface where most of the gain exists.

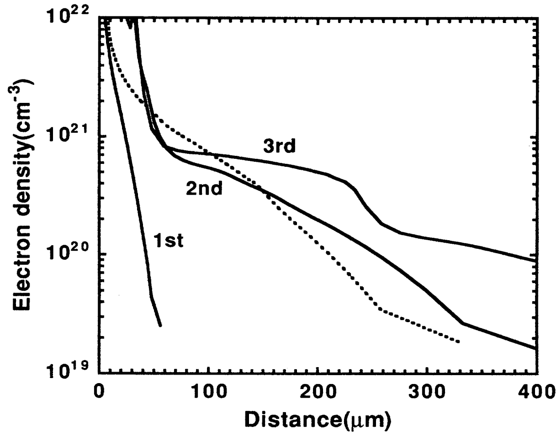

FIG. 2. Electron density versus distance from the surface of the slab in the direction of the hydrodynamic expansion. Two cases are shown: using multiple pulse illumination (solid) and single pulse illumination (dotted). The LASNEX calculations are at the time of peak illumination from the optical drive laser. For the multiple pulse case, the density is given at the three peaks labeled 1st, 2nd, and 3rd.

Using the LASNEX calculated densities and temperatures as input to the XRASER code [10], the gains of the laser lines were calculated including radiation trapping effects on the $3s \rightarrow 2p$ transitions in Ne-like Se. Bulk Doppler effects due to the expansion of the plasmas were also included. Figure 3 plots contours of the gain versus space and time for the 182 and 209 Å lines for the case of multiple pulse illumination. For both lines the gain region is very small and short lived during the first Nova pulse, which peaks at 150 ps on this scale. During the second and third pulses, which peak at 550 and 950 ps, the gain of the 182 Å line is seen to be larger, peak closer to the surface, occur earlier in time, and have a shorter time duration than for the 209 Å line. The 182 Å line is driven by direct collisional excitation and is seen to lase when the Nova drive pulse is heating the plasma while the 209 Å line tends to peak after the drive pulse and have a longer time duration as would be expected for a laser line which is driven by recombination and cascade processes [11]. These general characteristics are consistent with our experimental observations; however, spatially resolved measurements of the laser lines which are absolutely timed are needed to better compare with our modeling. The fact that the analogous lines in Ge at 196 and 236 Å had measured gains which were very similar in spite of the 196 Å line being much brighter than the 236 Å line is no doubt due to the fact that the gain measurements were time-integrated, spatially integrated measurements of the effective gain including

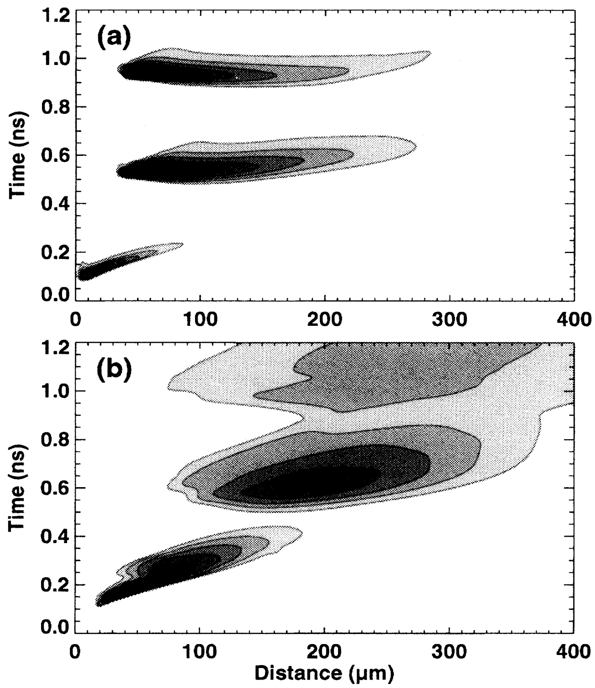

FIG. 3. Contours of gain versus space and time for the 182 Å (a) and 209 Å (b) laser lines as calculated by the XRASER code using the hydrodynamic simulations from LASNEX as input for the case of multiple pulse illumination. Contours represent 15% and 12% changes, respectively. The darkest region for the 182 Å line represents gain greater than 24 cm^{-1} while the same darkness represents gain greater than 7 cm^{-1} for the 209 Å line.

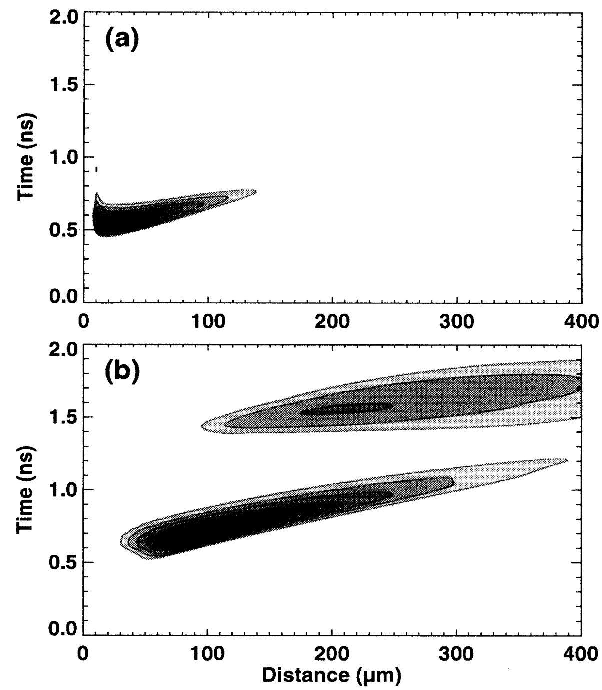

FIG. 4. Contours of gain versus space and time for the 182 Å (a) and 209 Å (b) laser lines as calculated by the XRASER code using the hydrodynamic simulations from LASNEX as input for the case of single pulse illumination. Contours represent 9% and 11% changes, respectively. The darkest region for the 182 Å line represents gain greater than 13.5 cm^{-1} while the same darkness represents gain greater than 5.5 cm^{-1} for the 209 Å line.

loss mechanisms such as refraction. The actual small signal gain of the 196 Å line is probably much larger as the calculations suggest, but the fact that the lasing region is smaller and the time duration is shorter combined with the larger refraction losses all combine to make the gains of the 196 and 236 Å lines appear similar for Ge.

For comparison, Fig. 4 plots contours of the gain versus space and time for the 182 and 209 Å lines for the case of long single pulse (600 ps) illumination of a Se slab target with the Nova pulse peaking at 900 ps. The gain of the 182 Å line peaks 15 μm from the surface at 550 ps while the 209 Å line has a first strong peak at 720 ps which is 100 μm from the surface. A second peak is predicted for the 209 Å line, but it is weaker and therefore unlikely to be observed.

When compared with long single pulse illumination of a slab target the short multipulse illumination offers several advantages. The first is the smaller density gradient in the lasing region, as seen in Fig. 2, which allows the x rays to propagate through more gain region. In addition, with single pulse illumination, most of the optical energy is deposited near the critical density surface (4×10^{21} electrons/cm^3) and the hot plasma expands to create an isothermal transparent plasma which tends to strip past the Ne-like stage as the optical laser continues to drive the high density part of the plasma. This is why both the 182 and 209 Å laser lines peak before the peak of the Nova pulse, as seen in Fig. 4. In contrast, with the multiple pulses, the first pulse heats, ionizes, and expands the plasma, but between pulses the plasma cools from approximately 1000 to 300 eV. This allows the plasma to recombine to Ne-like. However, the temperature is still high enough to ionize the Na-like ions and keep the plasma from recombining further. In addition, this cold plasma is not transparent to the optical drive laser, and energy from the subsequent optical pulses can be directly absorbed by the lasing region of the plasma during the rising edge of the optical pulse. The pulses can rapidly heat the plasma but do not have sufficient time to ionize the plasma significantly in the lasing region. So the multiple pulses help create stable regions of Ne-like ions which can absorb the subsequent pulses and lase. We use only three pulses but potentially this process could be repeated many times.

In conclusion, using short multipulse illumination of selenium targets, the neonlike selenium lasing is nearly monochromatic with the $J = 0 \rightarrow 1$, $3p \rightarrow 3s$ transition at 182 Å completely dominating the lasing output as was always predicted, but never observed before this work. The 182 Å line is an order of magnitude brighter than the usual 206 and 209 Å laser lines. Similar behavior is observed for neonlike ions of germanium, zinc, and nickel where the 196, 212, and 231 Å lines dominate the spectra of the respective ions. This multipulse technique enables one to generate short-duration, high-intensity, nearly monochromatic x-ray laser pulses which can be used as a strobe for imaging plasmas which are changing rapidly in time, an example being the plasmas studied in inertial confinement fusion research.

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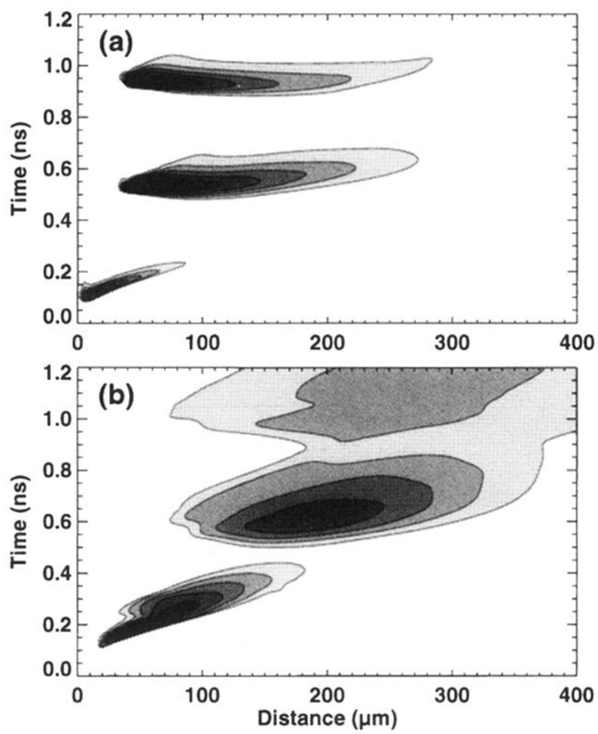

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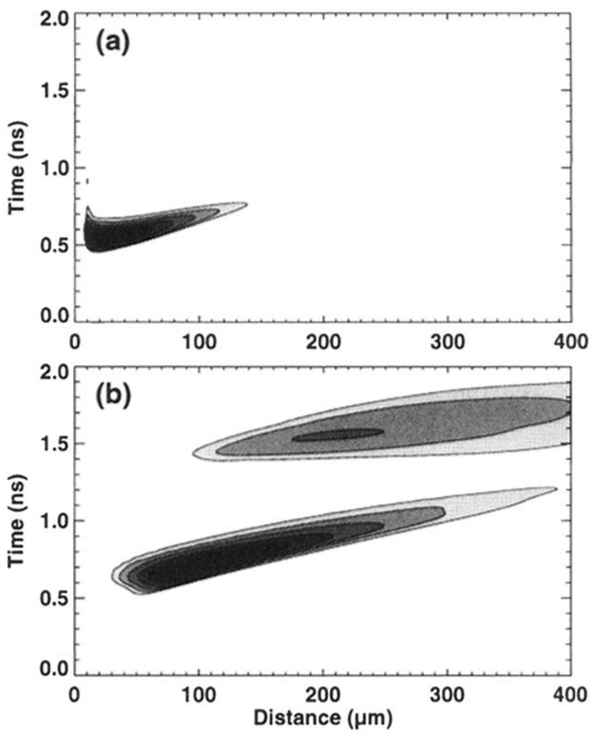

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