Demonstration of a Soft X-Ray Amplifier

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We report observations of amplified spontaneous emission at soft x-ray wavelengths. An optical laser ionized thin foils of selenium to produce a population inversion of the $2p^5 3p$ and $2p^5 3s$ levels of the neonlike ion. Using three time-resolved, spectroscopic measurements we demonstrated gain-length products up to 6.5 and gain coefficients of 5.5 ± 1.0 cm^{-1} for the $J=2$ to 1 lines at 206.3 and 209.6 Å. We also observed considerable amplification for the same transitions in yttrium at 155.0 and 157.1 Å.

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For over a decade there has been an intense search for a way to produce amplification of XUV or soft x-ray radiation. Several recent papers[1,2] review the progress of the theoretical and experimental efforts. In general, the literature lacks a conclusive or unrefuted demonstration of such amplification.

One of the proposed methods of producing an XUV amplifier uses a high-power optical laser to directly heat a plasma. Using this technique, Zherikhin, Koshelev, and Letokhov[3] first described a mechanism for obtaining an inversion between $2p^5 3p$ and $2p^5 3s$ levels in neonlike ions. Vinagradov and co-workers[4] have subsequently written a series of papers refining the theoretical description. To produce the inversion, the $n=3$ excited levels are populated by electron impact excitation from the ground ($2p^6$) state of the neonlike ion, which is itself produced in the plasma heated by the optical laser. The population inversion between $2p^5 3p$ and $2p^5 3s$ levels develops because of the large difference between the radiative decay rates. Recent calculations[5–9] have extended this neonlike excitation scheme to ions in which the lasing wavelengths approach the soft x-ray regime.

The purpose of this Letter is to report the first results from new experiments on the neonlike collisional excitation scheme. We describe the first conclusive demonstration of a macroscopic-sized gain medium which exhibits substantial amplification of at least four $2p^5 3p$-$2p^5 3s$ transitions in selenium, with the largest being observed for the $J=2$ to 1 lines at 206.3 and 209.6 Å. The transition with the largest predicted gain,[4–9] the $J=0$ to 1 transition at approximately 183 Å, has not been uniquely identified. We base our conclusions on the results of over 100 separate laser-irradiated target experiments. We used a variety of spectroscopic instruments to measure the time-resolved absolute brightness of the amplified spontaneous emission (ASE), and to demonstrate the nonlinear increase of the emission with increased length of the gain medium. The anisotropy of the ASE was also verified by measurement of the relative intensity in the axial direction and in another direction far off that axis.

These x-ray laser experiments were conducted at the Novette laser-target irradiation facility. A simplified schematic representation of the experimental arrangement is shown in Fig. 1. The exploding-foil target design[10] is based on experience with long density-scale–length plasmas that are produced in inertial-confinement fusion research. Typically, the target was composed of a 750-Å layer of Se, vapor deposited on *one* side of a 1500-Å-thick Formvar substrate. The foil was nominally 1.1 cm long and was illuminated by green light ($\lambda = 0.532$ μm) along a line focus with dimensions of 0.02×1.12 cm. The nominal pulse length was 450 psec, and the typical incident intensity was 5×10^{13} W/cm^2. The targets were irradiated in two different geometries: "single-sided" in which a given segment of the foil was hit by only one laser beam, and "double-sided" in which opposing laser beams irradiated a common target area. Using the single-sided geometry we were able to illuminate targets up to 2.2-cm long by displacing the two beams axially.

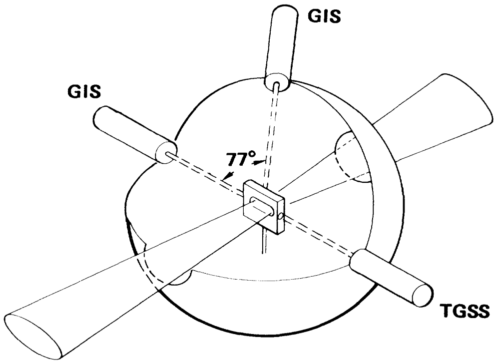

FIG. 1. Placement of primary diagnostics used in this experiment.

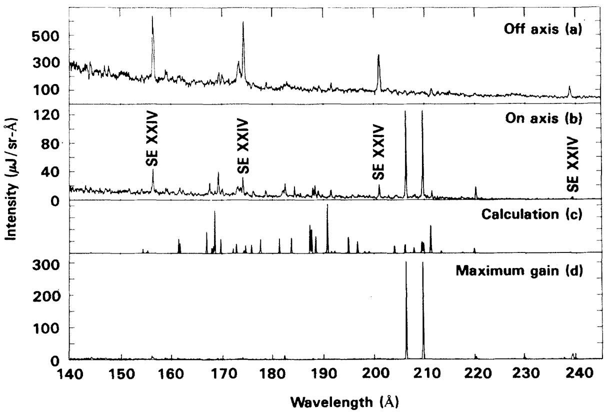

FIG. 2. (a) Grazing incidence spectrograph (GIS) data from off-axis line of sight. Data taken from beginning of radiative output until 500 psec after peak of pump laser. (b) On-axis GIS data from same time interval as (a). (c) Calculated spontaneous spectrum of neonlike selenium. (d) On-axis GIS data from maximum gain target.

X-ray emission in the two axial directions (see Fig. 1) was measured by use of a grazing incidence spectrograph (GIS) and a transmission grating spectrograph (TGSS). The GIS has high spectral resolution ($\lambda/d\lambda = 1800$) and a line-radiation-detection threshold of 6 erg/sr. It utilizes a microchannel plate contoured to the Rowland circle for detection of the x-ray spectra. Gating the microchannel plate detector by an Auston switch allowed viewing of the spectrum for a limited period of time (250–750 psec), thereby discriminating against emission occurring late in the experiment. The TGSS has a spectral resolution of $\lambda/d\lambda = 200$, detection threshold of 3.9 mW/Å (radiated into a solid angle of $\sim 1.1\times10^{-4}$ sr), and temporal resolution of 20–30 psec. The instrument incorporates an ellipsoidal collection optic, a 2000-Å period transmission grating, and a soft x-ray streak camera. In addition to the emission along the target's longitudinal axis, we recorded the spectrum at 77° off axis using another GIS which viewed the entire target.

In the course of the experiments we measured strong anisotropy of certain lines emitted from the exploding foils. Figures 2(a) and 2(b) illustrate spectral data monitored by the two GIS in the same time segment. Note the presence of Na-like resonance transitions (not expected to be amplified) both on and off axis, whereas the strong lines at 206.3 and 209.6 Å are *only* seen on axis. Based on *ab initio* calculations and isoelectronic extrapolation[11] from lower Z, these lines are positively identified as the $(2p_{3/2}3p_{3/2})_{J=2}$-$(2p_{3/2}3s)_{J=1}$ and $(2p_{1/2}3p_{3/2})_{J=2}$-$(2p_{1/2}3s)_{J=1}$ transitions of Ne-like Se, respectively. With the exception of the $3d_{3/2}$-$3p_{3/2}$ transition at 178.6 Å, the Na-like lines are optically thick and appear brighter off axis because the GIS views a larger surface area of the plasma in that direction.

In Fig. 2(c) we plot a theoretical *spontaneous*-emission spectrum of Ne-like transitions calculated under the assumption of an optically thin plasma in steady state at $T_e = 1.0$ keV and $N_e = 1\times10^{21}$ cm^{-3}. In the experimental spectra, the 206.3- and 209.6-Å lines

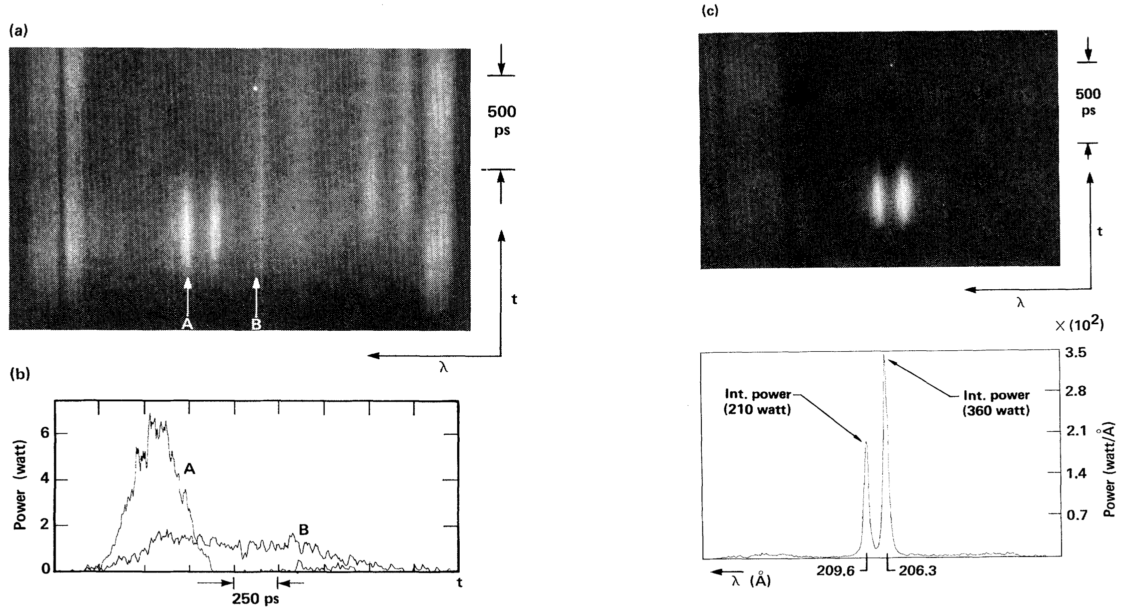

FIG. 3. (a) Film data from the TGSS for a moderate gain target. (b) Temporal profiles of the neonlike 209.6-Å lasing line (A) and the Na-like 201.1-Å line (B). (c) Film data from TGSS for a maximum gain target, and power vs wavelength.

are much stronger than all of the other nonlasing neonlike transitions which have larger *gf* values, e.g., the $2p^5 3d$-$2p^5 3p$ lines at 191.5, 188.4, and 169.2 Å (see Ref. 11). The dominance of the two $J=2$ to 1 lines in the spectrum was observed in approximately 100 laser shots.

Figure 2(d) illustrates the maximum amplification we obtained in these experiments. In this case the target was shot single sided at an incident intensity of 1×10^{14} W/cm^2, but with the beams displaced to give a total amplification length of 2.2 cm. It is important to note that we do not observe a strong line near 183 Å, the predicted position of the transition with the largest calculated[4-9] gain $[(2p_{1/2}3p_{1/2})_{J=0}$-$(2p_{1/2}3s)_{J=1}]$. If there were little or no amplification of this transition, it could not be seen because of its small *gf* value.[5,8,11]

Figure 3 illustrates the temporal behavior of the emission as recorded by the TGSS. Figure 3(a) shows film data obtained with a 1.0-cm target displaying moderate amplification. In Fig. 3(b) the temporal profile of the amplified line at 209.6 Å is compared with that of the spontaneous emission of the Na-like ion at 201.1 Å. Note that the time duration of the amplified emission is significantly shorter than that of the nearby spontaneous lines as well as the pulse width of the pump laser. With increased amplification, the pulse widths of the lasing lines tend to decrease. Figure 3(c) shows film data obtained with a 2.2-cm target for which the amplification is large. Also shown is a spectral profile taken at the time of peak ASE. The width of the line, which is source-size broadened, is ~1.0 Å indicating a source region of ~200-μm diameter. Figure 3(c) gives a strong indication of nonequilibrium conditions in the plasma. If we assume that the 206.3-Å line is Doppler broadened, with a width of 0.04 Å ($T_{\rm ion}\simeq 400$ eV), then we obtain ~40 keV for the equivalent brightness temperature. In contrast, the brightness temperature inferred from the Na-like emission at 201.1 Å is ~0.1 keV.

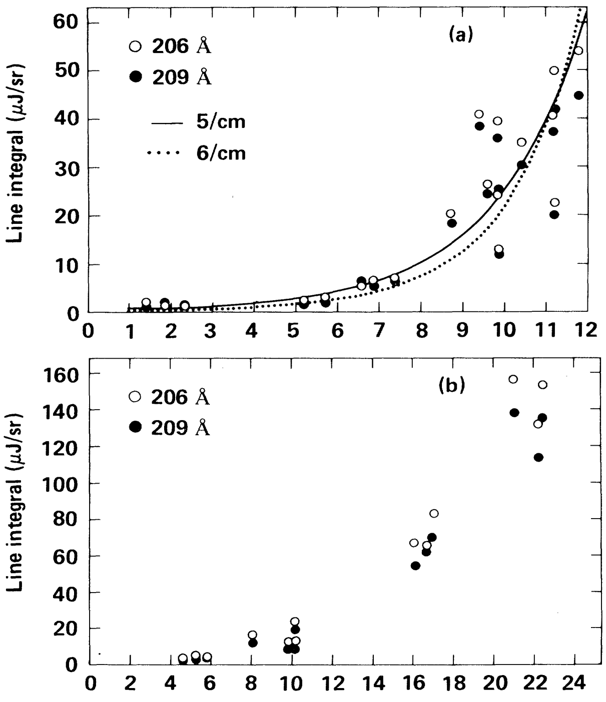

FIG. 4. Integrated line intensity of $J=2$ to 1 transitions vs amplifier length for (a) double-sided and (b) single-sided laser irradiation conditions.

The most quantitative evidence for amplification is shown in Fig. 4. These results come from the axial GIS and are integrated over the linewidths of the 206.3- and 209.6-Å transitions. The data exhibit a nonlinear dependence on the length of the amplifier. The output intensity (integrated over frequency) emitted by a one-dimensional homogeneous gain medium of length L under steady-state conditions scales as $\exp(\alpha L)L^{-1/2}$, where α is the line-center gain coefficient. This scaling is valid when $\alpha L \geqslant 2$. Fitting the data from double-sided shots with this expression yields a gain coefficient of $\alpha = 5.5\pm1.0$ cm^{-1} for both the 206.3- and 209.6-Å lines. Although the data obtained with single-sided irradiation demonstrates significant amplification, up to 700 times spontaneous levels, the complexity of both the target irradiation geometry and the radiation transport preclude simple modeling of the length dependence. Note also that the behavior of the data as a function of length indicates the amplifier is *below* saturation. Future experiments will be aimed at achieving saturation of the amplifier and improving the efficiency from the present value of approximately 10^{-10}. (Efficiency is the energy radiated by the lasing transition divided by the incident optical laser energy.)

In addition to the measurements described above, we have done preliminary experiments to produce amplification at shorter wavelengths. In particular, we irradiated yttrium foil targets and observed amplification of the $J=2$ to 1 neonlike transitions at 155.0 and 157.1 Å. Once again, the neonlike $J=0$ to 1 transition was not observed. Just as for selenium, the yttrium emission exhibited strong anisotropy, short time duration, and a brightness temperature of ~5 keV (155.0-Å line).

In conclusion, by using an optical laser to produce a population inversion in a simple exploding foil, we have demonstrated substantial amplification of spontaneous emission at soft x-ray wavelengths.

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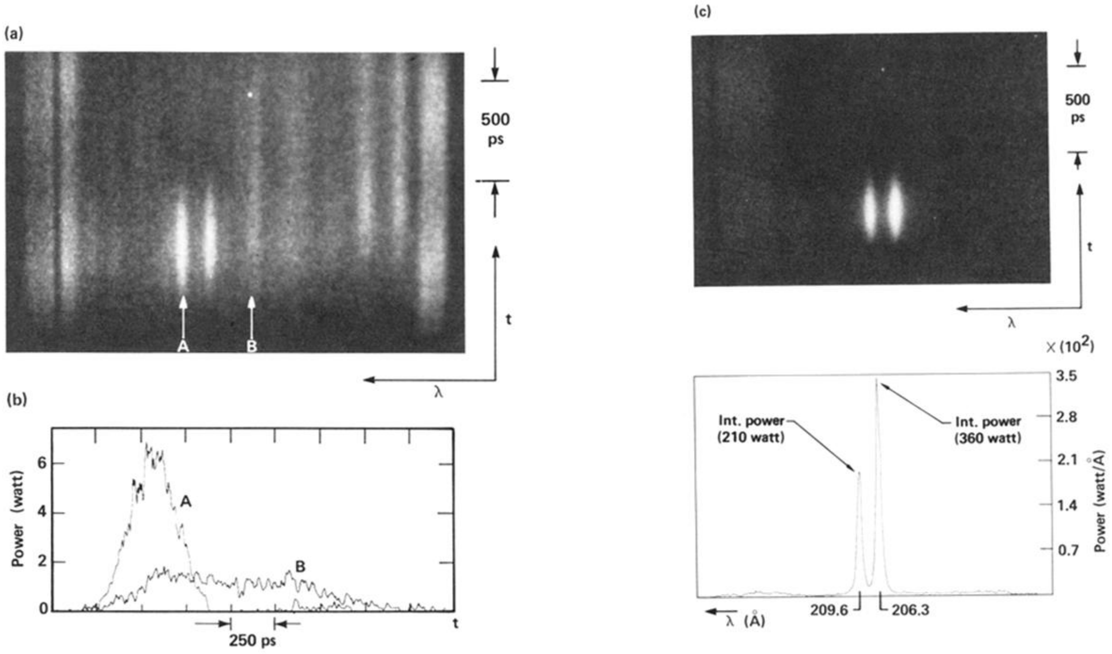

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