Resonantly photopumped Ni-like Er x-ray laser

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This paper presents a laboratory x-ray laser that lases on several $4d \rightarrow 4p$ transitions ranging from 54 to 89 Å in nickel-like erbium ($Z=68$) and that is resonantly photopumped by the $2p_{1/2} \rightarrow 1s_{1/2}$ emission line, Lyman-α, in hydrogenlike aluminum. The Al-Er scheme has a tremendous advantage in that it enhances the gain of laser lines that would be expected to lase from collisional excitations and recombination processes; therefore it should be much easier to observe the photopumping process, as it will increase an already finite exponential gain. The resonant photopumping process is also shown to create gain on one additional laser line that has not previously appeared in the Ni-like spectra. Calculations of the gain of these laser transitions in steady-state equilibrium plasmas are presented.

I. INTRODUCTION

Since the first successful demonstration of x-ray lasing was achieved in Ne-like selenium on the $3p \rightarrow 3s$ transitions ($\lambda \approx 200$ Å) using collisional excitation as the pumping mechanism,[1,2] there have been several other demonstrations of lasing in the soft x-ray region using either collisional excitation or recombination as the pumping mechanism.[3-9] Recent experiments have demonstrated even shorter wavelength lasing by using the $4d \rightarrow 4p$ transitions ($\lambda \approx 65$ and 50 Å) in Ni-like Eu ($Z=63$) and Ni-like Yb ($Z=70$), respectively.[8,9] Other mechanisms such as photoionization[10-14] and resonant photopumping[15-25] have been proposed as possible candidates to build an x-ray laser. However, the resonant photopumping mechanism has not yet been demonstrated in the soft x-ray region. The shortest wavelength at which significant gain has been measured using resonant photopumping is at 2163 Å in Be-like C.[26] This paper describes a new x-ray laser scheme, which would lase on several $4d \rightarrow 4p$ transitions ranging from 54–89 Å, based on resonant photopumping of Ni-like Er ($Z=68$) using the $2p_{1/2} \rightarrow 1s_{1/2}$ emission line, Lyman-α, from H-like Al. The resonant photopumping is shown to enhance the gain of several laser lines, which are expected to lase due to collisional pumping and recombination processes, as well as creating gain on one additional laser line which has not previously appeared in the Ni-like spectra.

II. BASIC LASER SCHEME

The basic resonant photopumping scheme, using the 64.8 Å laser line as an example, is shown in Fig. 1. The process consists of the Al XIII Ly-α emission line resonantly photopumping an electron in the ground state to the $\overline{3d}_{3/2}4f_{5/2}(J=1)$ level of Ni-like Er. This transition in Ni-like Er is the strongest transition with an oscillator strength of 6.6. This $4f$ level decays directly to the $\overline{3d}_{3/2}4d_{3/2}(J=1)$ level, which is the upper laser state. Lasing occurs between the $4d_{3/2}$ and $4p_{1/2}$ states. The lower laser state then decays back to the ground state. In Fig. 1 are also shown the most important kinetic rates in Ni-like Er which are relevant for producing gain in the 64.8 Å laser line. The radiative rates are denoted by γ^R while the collisional rates are given by γ^C. A pump strength of 0.005 photons per mode, defined by Eq. (1), is assumed for the Al pump line. A simple geometry for demonstrating this laser consists of a double sided foil of Er and Al which is irradiated on both sides by two beams from a high-power optical laser such as NOVA II.

In Ni-like Eu five laser lines have been observed due to the collisional excitation and recombination processes. In the Ni-like Er one would expect to see these five lines in the absence of the Al pump. With the Al pump present four of these lines should be significantly enhanced and a new laser line at 64.8 Å should also appear. The six laser lines, along with the calculated wavelengths of the laser transitions, are given in Table I. The

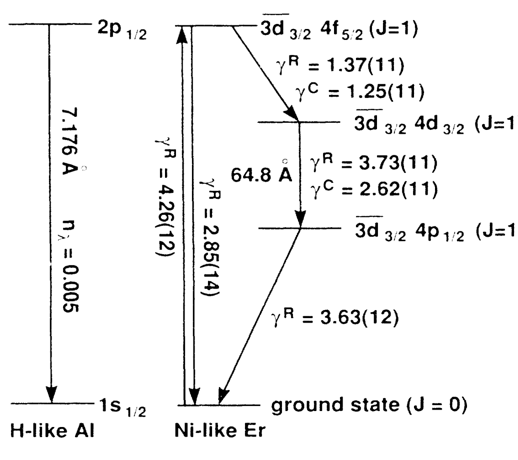

FIG. 1. Kinetic rates (sec^{-1}) relevant for the 64.8-Å lasing transition in the Al-Er x-ray laser.

TABLE I. Laser transitions for Ni-like Er.

Transition	Wavelength (Å)	Gain (cm^{-1}) for n_λ $=0.000$	$=0.002$	$=0.005$	$=0.010$
$\overline{3d}_{3/2}4d_{3/2}(J=0)\rightarrow\overline{3d}_{3/2}4p_{1/2}(J=1)$	54.3	3.04	3.57	4.32	5.44
$\overline{3d}_{3/2}4d_{3/2}(J=0)\rightarrow\overline{3d}_{5/2}4p_{3/2}(J=1)$	59.9	3.45	4.15	5.12	6.58
$\overline{3d}_{3/2}4d_{3/2}(J=0)\rightarrow\overline{3d}_{3/2}4p_{3/2}(J=1)$	75.3	0.71	0.86	1.07	1.39
$\overline{3d}_{5/2}4d_{5/2}(J=2)\rightarrow\overline{3d}_{5/2}4p_{3/2}(J=1)$	86.0	6.50	6.59	6.72	6.91
$\overline{3d}_{5/2}4d_{5/2}(J=1)\rightarrow\overline{3d}_{5/2}4p_{3/2}(J=1)$	89.6	4.62	5.40	6.49	8.12
$\overline{3d}_{3/2}4d_{3/2}(J=1)\rightarrow\overline{3d}_{3/2}4p_{1/2}(J=1)$	64.8		0.75	3.41	7.38

bar over the $3d$ states represents a single electron hole in an otherwise closed M shell $[1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}]$ configuration or nickel-like core. The calculated energies have been lowered by 7.0 eV for the $(J=0)$ transitions, before being converted to wavelengths, to approximate the observed corrections between theory and experiment for Ni-like Eu and Ni-like Yb.

III. RESONANCE CONDITION AND PUMP STRENGTH

To enhance the gain in Ni-like Er by resonant photopumping with the Al XIII Ly-α emission line a strong Al pump line is needed which is resonant with the Ni-like Er line and which is present in the plasma at the same time as the Ni-like Er ions.

The H-like Al $2p_{1/2}\rightarrow 1s_{1/2}$ pump line is calculated[27] to be at 7.176 32 Å while the ground state to the $\overline{3d}_{3/2}4f_{5/2}(J=1)$ transition in Ni-like Er is calculated to be at 7.176 Å using the multiconfiguration Dirac-Fock (MCDF) atomic physics code of Grant.[28] The $\overline{3d}_{3/2}4f_{5/2}(J=1)$ to ground-state line has been seen in many Ni-like plasmas[29–32] but there has been no published data for Er yet. Several approaches can be used to give one confidence in the resonance. First, the experimental measurements[29,30] of the ground state to the $\overline{3d}_{3/2}4f_{5/2}(J=1)$ transition in Ni-like ions for $Z=69$–75 can be extrapolated to $Z=68$ by fitting the data to a straight line as described in Ref. 30. The extrapolation yields a value of 7.178 Å, which is only 2 mÅ from the theoretical prediction. A second approach is to compare the theoretical calculations using the MCDF code with experimental measurements. For $Z=69$ and 70, the theoretical values calculated with the MCDF code agree with the measured values[29] to better than 1 mÅ. The experimental measurements are made with an accuracy of better than 5 mÅ, so one can conclude that the Er resonance should be good to less than 5 mÅ, which is better than 1 part in 1000. Exactly, how good a resonance is required depends on the linewidth of the Al XIII pump line.

The full width half maximum (FWHM) Doppler width for the Al line in a plasma with an ion temperature of 450 eV is 2.3 mÅ. The actual linewidth for an optically thick pump line will be further broadened by opacity broadening. An opacity broadened linewidth, with an upper bound of 35 mÅ, has been measured for a Na X He-α line[21] at 11 Å while a 14 mÅ linewidth has been observed for a Al XIII Ly-β line[25] at 6 Å. If an exploding foil is used for the Al, there may be additional bulk Doppler shifts. The other strong H-like Al $2p_{3/2}\rightarrow 1s_{1/2}$ line is at 7.170 92 Å. In addition there are satellite lines present which will all contribute to a broader and stronger pump line. It should be pointed out that other strong emission lines could be used to pump Ni-like ions if a suitable resonance can be identified for a particular pair of pump and lasant ions.

Calculations which have been done on Al targets[24] predict Al XIII Ly-α radiation with brightnesses of 0.002 to 0.005 photons per mode and a FWHM of 8–20 mÅ for incident optical laser intensities from $(0.3-2)\times10^{15}$ W/cm^2. The spectral intensity I_λ of the pump line, where $I_\lambda\Delta\lambda$ is the power per unit area, is calculated from the modal density n_λ, in photons per mode, by

$$I_\lambda = 8\pi c\frac{hc}{\lambda^5}n_\lambda = \frac{1.497\times10^{18}}{\lambda^5}n_\lambda \quad (1)$$

in W/cm^2 mÅ, where λ is the photon wavelength in Å, c is the speed of light, and h is Planck's constant. At longer wavelengths the pump strengths have been measured,[19,23] with a value of 0.002 photons per mode measured for the 11-Å He-α line in Na X.

The ionization balance issue can easily be answered as H-like Al plasmas and Ni-like high-Z plasmas have been made routinely in the laboratory. In spectroscopic studies of Al, H-like Al[25,33] lines have been generated in plasmas with the electron temperature estimated to be 600 eV and the electron density 1×10^{22} cm^{-3}. The laser illumination was $(0.5-2)\times10^{15}$ W/cm^2 using a 0.53 μm laser pulse. For the Ni-like Eu and Yb lasers[8,9,34,35] which have been demonstrated, the electron temperature is estimated to be between 600 and 900 eV, with the electron density varying from $(0.2-1)\times10^{21}$ cm^{-3}. The laser illumination was $(0.7-1.4)\times10^{14}$ W/cm^2 using two beams of the 0.53 μm NOVA pulse.

IV. LASER GAIN CALCULATIONS

To understand what gain might be achieved in Ni-like Er by resonant photopumping, an atomic model of the Er was constructed using the atomic physics package YODA.[36] YODA was used to calculate energy levels, oscillator strengths, and collision strengths for the $n=3$ Co-like Er states and the $n=3$ and 4 Ni-like and the $n=4$ Cu-like Er states. These were combined with simple hydrogenic data for the rydberg states and the other nearby sequences. Using this atomic model as input, several steady-state XRASER calculations[37] were done assuming there was a strong H-like Al line available to pump the

Ni-like ground state to the $\overline{3d}_{3/2}4f_{5/2}(J=1)$ transition. The calculations were done with an Er ion density of 1.0×10^{19} ions/cm^3 and an electron density determined by the ionization of the Er. The electron temperature was fixed at 700 eV while an ion temperature of 450 eV was used. Under these conditions the fraction of ions in the Ni-like ground state is 21.6–24.4 % depending on the strength of the Al pump line. In Table I are shown the gains for the six principal Ni-like lines for several values of the Al pump line. The case without the line pump $n_\lambda=0$ corresponds to the usual collisionally pumped scheme. The most exciting line is the 64.8-Å line which goes from being an absorption line (with a loss of 1.14 cm^{-1}) to a gain line. Observing gain on this line would be clear verification of the resonant photopumping process. The first two lines at 54.3 and 59.9 Å have gain enhancements of 80% and 90%, respectively, as the pump strength is increased to 0.01 photons per mode. These two lines have been observed experimentally[8,9] to have gain in Ni-like Eu and Ni-like Yb and therefore would be expected to lase in Ni-like Er. A big advantage of this photopumping scheme is that it enhances the gain of laser lines which would be expected to lase from collisional excitations, therefore it should be much easier to observe the photopumping process even in the case of a weak pump line as photopumping will increase an already finite exponential gain. The lines at 75.3 Å and 89.6 Å are also significantly enhanced, by 100% and 80%, respectively. However, these lines have been observed experimentally to have weak gain. The photopumping may enable these lines to overcome the processes which are resulting in the experimental gain being much lower than the theoretical gain predictions. The other line at 86.0 Å is essentially uneffected by the photopumping.

V. CONCLUSIONS

This paper has described a laboratory x-ray laser which consists of a H-like aluminum $2p_{1/2}\rightarrow 1s_{1/2}$ emission line, Lyman-α, resonantly photopumping a ground state to $\overline{3d}_{3/2}4f_{5/2}(J=1)$ Ni-like Er transition resulting in gain on five laser lines ranging from 54–89 Å. The resonant photopumping is shown to significantly enhance the gain of four laser lines as well as creating gain on one additional laser line which has not previously appeared in the Ni-like spectra. The Al-Er scheme has the tremendous advantage in that it enhances the gain of laser lines which would be expected to lase from collisional excitations and recombination processes, therefore it should be much easier to observe the photopumping process even in the case of a weak pump line as photopumping will increase an already finite exponential gain.

It is hoped that this paper will stimulate research that will experimentally demonstrate for the first time a resonantly photopumped x-ray laser. Initially, experiments are needed to verify the Al-Er resonance and to identify other potential resonant pairs. Experiments are also needed to measure the strength and width of proposed pump lines such as the Al XIII Lyman-α line and to understand how to optimize the strength of these pump lines.

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