Self-photopumped neonlike x-ray laser

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We propose a new x-ray laser mechanism that uses radiation from the strongest $3d \rightarrow 2p$ Ne-like resonance line in an optically thick plasma to radiatively drive population from the Ne-like ground state to the $3d$ state, which then lases to two $3p$ states. Collisional mixing of the $3p$ states with nearby $3s$ and $3d$ states depopulates the lower laser states. Modeling is presented for this mechanism in Ne-like Ar, and in experiments we observe one potential $3d \rightarrow 3p$ lasing transition at 45.1 nm in Ne-like Ar.

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For the past two decades many scientists[1] have studied the resonant photopumping mechanism in the hope of developing a high-efficiency x-ray laser. However, the shortest wavelength at which significant gain has been measured by resonant photopumping is in Be-like C at 216 nm, far outside the x-ray region. The generic idea has been to find a strong pump line that is resonant with a line in the lasing material and that can be photopumped and thereby create a population inversion in the laser material. To overcome the difficulty of finding a good resonance between two different materials, several authors[2,3] have proposed self-pumping schemes in which two plasmas of the same material at different temperatures and densities are used, with the pump line in the hot dense plasma pumping the same line in the cooler lower-density laser plasma. In this Letter we propose a new approach, which is to use self-pumping of a strong emission line in an optically thick plasma to radiatively drive population into the upper laser state. The population of the lower laser state is then destroyed by collisional mixing with nearby states.

Using the $3d\,^1P_1 \rightarrow 3p\,^1P_1$ laser line at 45.1 nm in Ne-like Ar as an example, we show in Fig. 1 the lasing mechanism, which consists of the $3d\,^1P_1 \rightarrow 2p\,^1S_0$ line at 4.147 nm in Ne-like Ar resonantly photopumping an electron in the ground state of the Ne-like Ar ion to the $3d\,^1P_1$ upper laser state. For convenience we leave out the $1s^2 2s^2 2p^5$ electrons, which are common to all the levels, and use *LS* coupling notation. Lasing occurs between the $3d\,^1P_1$ and $3p\,^1P_1$ states. At the appropriate densities, the $3p\,^1P_1$ lower laser state is destroyed primarily by collisional mixing with the other nearby $3s$ and $3d$ states. It can also radiatively decay to the $3s\,^1P_1$ state, which then decays to the ground state. The $3d\,^1P_1$ state can also lase at 46.5 nm to the $3p\,^3P_1$ state. The $3d\,^1P_1$ state also decays strongly to the $3p\,^1S_0$ state and enhances the gain of the collisionally excited $3p\,^1S_0 \rightarrow 3s\,^1P_1$ transition at 46.9 nm and the weaker $3p\,^1S_0 \rightarrow 3s\,^3P_1$ transition at 43.1 nm.

Unlike other resonantly photopumped x-ray laser schemes, which require a strong pump line from a separate plasma that is resonant with a line in the laser medium, this scheme is self-pumped and therefore has perfect resonance. The proposed pump line is

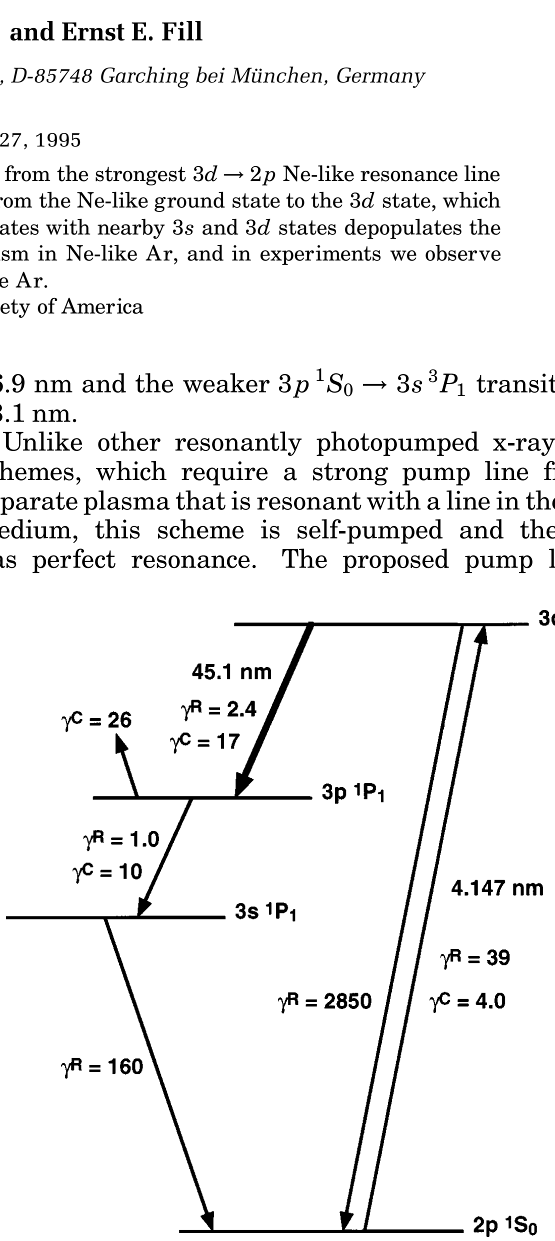

Fig. 1. Energy-level diagram showing the resonant photopumping mechanism for the 45.1-nm Ne-like Ar laser transition that is self-photopumped by radiation trapping of the strong $3d \rightarrow 2p$ resonance line at 4.147 nm. The important kinetic rates (ns^{-1}) are shown; the radiative rates are denoted by γ^R, and the net collisional rates by γ^C. The lasing process is driven by the photoexcitation rate, $\gamma^R = 39\ \text{ns}^{-1}$. The rates are in the region of peak gain from the detailed XRASER calculations, which include line transfer on the seven $n = 3 \rightarrow n = 2$ Ne-like lines.

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the strongest Ne-like line for $Z < 36$ and has an oscillator strength of approximately 2. This laser scheme is less susceptible to radiation trapping effects because the lower laser state is destroyed primarily by collisional mixing and it is not directly connected to the ground state by radiative decay. Since the $3d \rightarrow 2p$ pump line is the strongest Ne-like line it can be made much more optically thick than the other lines in the plasma, thereby enhancing its relative brightness. Under the appropriate plasma conditions, lasing could be achieved in many other Ne-like ions by this photopumping process.

To estimate the gain that can be achieved in this photopumped system we model an Ar plasma similar to that used in recent experiments[4] in which an Ar-gas puff target was illuminated from the side by line-focused 1.315-μm light with a width of 150 μm, a peak intensity of 19 TW/cm^2, and a pulse width of 450 ps. The Ar gas is assumed to have peak density of 0.15 mg/cm^3 on the laser axis and fall off in the direction of the laser illumination as a Gaussian with a $1/e$ width of 318 μm. LASNEX one-dimensional computer simulations, which include an expansion angle of 15 deg in the dimension perpendicular to the primary expansion so as to simulate two-dimensional effects, are used to calculate the time-dependent temperature and hydrodynamics of the Ar plasma.[5] These data are used as input to the XRASER kinetics and radiation transport code,[6] which calculates the time- and space-dependent gain of the laser lines including radiation transfer for all seven $n = 3 \rightarrow n = 2$ resonance lines in Ne-like Ar. The calculation shows the gain of the four strongest laser lines peaking 230 μm from the center of the plasma 250 ps before the peak of the laser drive pulse. In the region of peak gain the electron temperature is 222 eV, the ion temperature is 25 eV, and the electron density is 1.2×10^{19} cm^{-3}. The two photopumped $3d \rightarrow 3p$ laser lines at 45.1 and 46.5 nm have peak gains of 9.8 and 8.4 cm^{-1}, respectively. The 4.1-nm pump line is 90 optical depths from the low-density edge of the plasma and has a radiation temperature of 55 eV, which strongly populates the $3d$ upper laser state. In contrast, the $3p$ lower laser states have populations that correspond to an excitation temperature of 42 eV compared with the Ne-like ground-state population. The excited states have much lower populations than the electron temperature would suggest because this is a coronal plasma in which the rapid radiative decay of the $n = 3$ states to the Ne-like ground state is much faster than collisional depopulation. This is no surprise since the reason that these plasmas lase is that they are not in equilibrium. If we do the XRASER calculation with the line transfer package turned off so that the lines are optically thin, then both $3d \rightarrow 3p$ lines become slightly absorbing. The $3p$ lower laser states now have populations that correspond to an excitation temperature of 37 eV, but the $3d$ upper laser state has a population that corresponds to an excitation temperature of 40 eV. Table 1 shows the gain for the four strongest laser lines for these two cases in the region of peak gain. The gains of the normal collisionally pumped $3p \rightarrow 3s$ laser lines at 46.9 and 43.1 nm are large for both cases but are enhanced by the photopumping process. Radiation trapping by the $3s \rightarrow 2p$ transition, whose radiation temperature is only 41 eV, has a small effect on the gain.

Under the plasma conditions at the peak of the gain region described above, Fig. 1 shows the radiative and net collisional rates, γ^R and γ^C, respectively, in inverse nanoseconds. We calculate the net collisional rates by taking the population flux between the levels and dividing by the population of the initial level. To populate the $3d$ upper laser state, the radiative rate from the ground state that is due to the radiative field is more than an order of magnitude larger than the collisional excitation rate. Among the $n = 3 \rightarrow 3$ transitions, the collisional rates dominate. In particular, the net collisional rate from the $3p$ lower laser state to the other $3s$ and $3d$ states is 15 times larger than the spontaneous emission rate on the laser transition. The $3p$ lower laser state is populated primarily by collisional mixing and radiative decay from the $3d$ upper laser state. In the absence of the radiation field, the net fluxes among the laser states change direction, and the $3p$ lower laser state is then populated primarily by collisional excitation from the ground state and the $3s$

Table 1. Gains of the Four Ne-Like Ar Laser Transitions in the Region of Peak Temporal and Spatial Gain[a]

		Gain (cm^{-1})	
		Line Transfer	
Transition	λ (nm)	On	Off
$3d\,^1P_1 \rightarrow 3p\,^1P_1$	45.1	9.8	−0.5
$3d\,^1P_1 \rightarrow 3p\,^3P_1$	46.5	8.4	−0.5
$3p\,^1S_0 \rightarrow 3s\,^1P_1$	46.9	28.7	22.7
$3p\,^1S_0 \rightarrow 3s\,^3P_1$	43.1	9.6	6.8

[a] Values are calculated with the LASNEX and XRASER codes for the two cases in which the line transfer calculation is turned on or off for the seven $n = 3 \rightarrow n = 2$ Ne-like lines. Self-photopumping of the $3d \rightarrow 2p$ line owing to radiation trapping in the optically thick Ar plasma drives the gain of the two $3d \rightarrow 3p$ laser lines. The $3p \rightarrow 3s$ lines are driven primarily by direct collisional excitation of the monopole transition from the ground state.

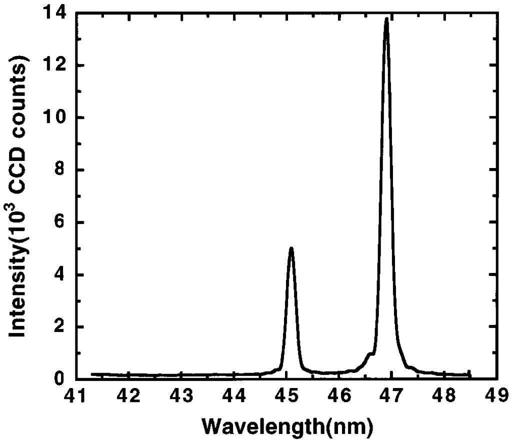

Fig. 2. On-axis spectrum obtained in Asterix experiments from a 2.7-cm-long target with an Ar-gas puff illuminated by a 400-J pulse with a duration of 450 ps. Two strong lines are observed, at 46.9 and 45.1 nm.

states and depopulated by collisional mixing with the $3d$ upper laser state and other $3d$ states. The collisional mixing is trying to equilibrate the populations among the $3s$, $3p$, and $3d$ levels. The presence of the strong radiation field pumping the $3d$ upper laser state drives the system further out of equilibrium and creates the strong gain on the $3d \rightarrow 3p$ lines.

Lasing on the Ne-like $3p\,^1S_0 \rightarrow 3s\,^1P_1$ transition at 46.9 nm was observed in recent experiments with an Ar-gas puff as the laser target. This $J = 0 \rightarrow 1$ line has been observed to lase in many low-Z Ne-like ions.[7–9] The surprising result in the Ar experiments was that another strong line appeared at 45.09 nm. We believe this line to be the $3d\,^1P_1 \rightarrow 3p\,^1P_1$ transition, which is lasing because of the self-photopumped process described in this study. Figure 2 shows a time-integrated, on-axis spectrum for a 2.7-cm-long Ar-gas puff target plasma irradiated by a 400-J, 450-ps pulse from the Asterix laser (1.315 μm) that is focused to a 3-cm-long by 150-μm-wide line. The 45.1-nm line is seen quite strongly near the 46.9-nm laser line. Both lines completely overshadow the continuum emission, which is less than 200 counts in Fig. 2. The spatially resolved data show both lines coming from the same plasma region. The 45.1-nm line disappears when shorter targets are used, so a measurement of the gain has not yet been possible. Beam-foil experiments done on a 2.5-MeV Van de Graff accelerator have shown the $3d\,^1P_1 \rightarrow 3p\,^1P_1$ transition at 45.08 ± 0.02 nm.[10–12] The same studies show that the other prospective laser line, the $3d\,^1P_1 \rightarrow 3p\,^3P_1$ transition, is at 46.5 nm. Neither this line nor the other $3p \rightarrow 3s$ line at 43.1 nm is observed in the laser experiments. Given the limited spectral resolution of the spectrometer as a result of source broadening it may be hard to resolve a weak 46.5-nm line in the wings of the strong 46.9-nm laser line.

In conclusion, we propose a self-photopumped x-ray laser scheme that uses radiation trapping of the strong Ne-like $3d \rightarrow 2p$ resonance line to create a strong radiation field that directly photopumps sufficient population from the Ne-like ground state to the $3d$ upper laser state to create a population inversion on the $3d \rightarrow 3p$ transition. The $3p$ lower laser state is depopulated by collisional mixing with nearby $3s$ and $3d$ states. This generic scheme should work for many low-Z Ne-like ions in which the $3d \rightarrow 3p$ resonance line can be made sufficiently bright and the appropriate temperatures and densities can be found for lasing. Recent x-ray laser experiments that used an Ar-gas puff target showed strong emission on this $3d \rightarrow 3p$ transition at 45.1 nm. We plan to measure the gain of this line and to look for lasing on this line in nearby elements. This generic scheme should also work in other ionization stages. In Ne-like ions the analogous process would be lasing on the $4f \rightarrow 4d$ transitions resulting from photopumping by the strong $4f \rightarrow 3d$ lines.

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