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Self photo-pumped neon-like and nickel-like X-ray lasers

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Self photo-pumped neon-like and nickel-like X-ray lasers

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Abstract. A new X-ray laser mechanism is presented which uses radiation trapping of the strongest 3d → 2p neon-like resonance line in an optically thick plasma to create an intense radiation field which radiatively drives population from the neon-like ground state to the 3d state, which then lases to a pair of 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 neon-like argon. Strong gain is predicted on the two 3d → 3p transitions at 45.1 nm and 46.5 nm, the first of which has been observed in recent X-ray laser experiments using an argon gas puff. The 3d → 3p line has also been observed at 60 and 30 nm, respectively, in X-ray laser experiments recently done on sulfur targets using the prepulse technique and on titanium targets driven by a nsec pulse followed by a psec pulse. This pumping mechanism also enhances the gain of the two 3p → 3s, J = 0 → 1 transitions which are at 43.1 and 46.9 nm in argon. This generic scheme can also work in other ionization stages. In nickel-like ions, the analogous process of lasing on the 4f → 4d transitions due to photo-pumping by the strong 4f → 3d lines will be discussed.

1. Introduction

For the last two decades many scientists have studied the resonant photo-pumping mechanism in the hope of developing a high-efficiency X-ray laser. In this paper we propose a completely new approach to photo-pumping 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, which lases to the lower laser state, whose population is destroyed by collisional mixing with nearby states. The radiation field of the strong pump line is enhanced by radiation trapping of the line in a optically thick plasma. For a plasma with the right temperature, density, and optical thickness, this scheme should work for many different ionization stages.

2. Basic Laser Scheme

Using the 3d $^1P_1$→ 3p $^1P_1$ laser line at 45.1 nm in neon-like argon as an example, Fig. 1 shows the lasing mechanism which consists of radiation from the 3d → 2p line at 4.147 nm in neon-like argon resonantly photo-pumping an electron in the ground state of the neon-like argon ion to the 3d $^1P_1$ upper laser state which lases to the 3p $^1P_1$ state. At the appropriate densities, the 3p lower laser state is primarily destroyed by collisional mixing with the other nearby 3s and 3d states. 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 → 3s , J = 0 → 1 transitions at 43.1 and 46.9 nm. Unlike other resonantly photo-pumped X-ray laser schemes which have been proposed and require a strong pump line from a separate plasma which is resonant with a line in the laser medium, this scheme is self pumped and therefore has a perfect resonance.

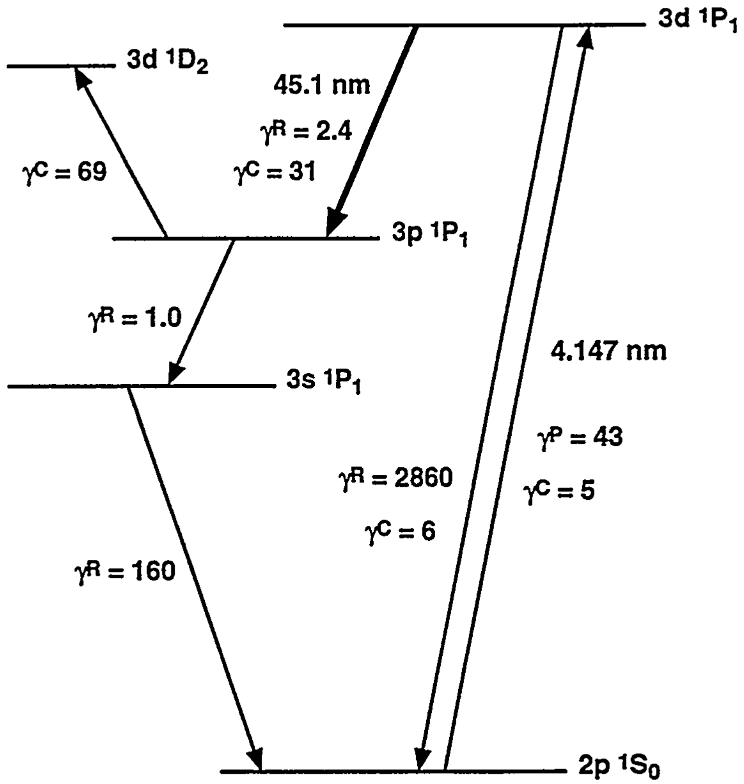

Fig. 1. The photo-pumping mechanism for the 45.1 nm neon-like argon laser transition.

3. Atomic Physics Model and Plasma Modeling

To estimate the gain, we modeled an argon plasma similar to that used in recent experiments at the Asterix laser facility where a 3 cm long by 400 μm wide nozzle was used to create an argon gas puff target which was illuminated from the side by line focused 1.315 μm light from a 400 J pulse with duration 450 ps and peak intensity of 19 TW/cm^2 . The argon gas is assumed to have peak density of 0.15 mg per 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(1D) computer simulations, which include an expansion angle of 15 degrees in the dimension perpendicular to the primary expansion so as to simulate 2D effects, are used to calculate the time dependent temperature and hydrodynamics of the argon plasma which are used as input to the XRASER code. The XRASER kinetics and radiation transport code then 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 neon-like argon. The YODA code is used to create the atomic physics model used as input to XRASER.

The gain of the 45.1 nm laser line peaks about 200 - 220 μm from the center of the plasma 250 ps before the peak of the laser drive pulse, with peak gain of 10.6 cm^{-1}. At the time of peak gain, Fig. 2 plots the gain of the 45.1 nm line(solid curve) versus distance from the center of the gas puff. For the case when we redo the calculation with the radiation transport turned off so that all the radiation is optically thin, including the pump line, the 45.1 nm line becomes slightly absorbing, as shown by the dotted line in Fig. 2. In the region of peak gain the electron temperature is 229 eV, the ion temperature is 27 eV, the electron density is 1.3 x 10^{19} cm^{-3} and the electron density gradient is -6 x 10^{20} cm^{-4}. A 45.1 nm laser photon will only be refracted 25 μm over a distance of 3 cm for this small gradient. This is much less than the spatial extent of the gain region. The 4.147 nm pump line is 110 optical depths from the low density edge of the plasma and has a radiation temperature of 56 eV which strongly

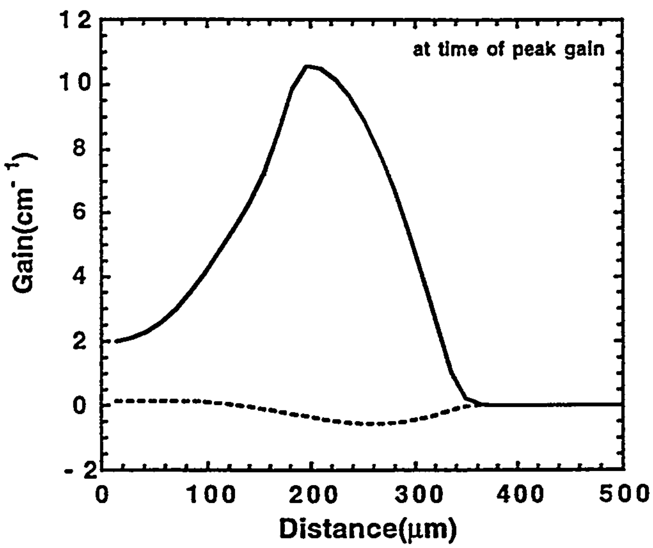

Fig. 2. Gain of the 45.1 nm laser line vs distance from the center of the gas puff.

populates the 3d upper laser state. In contrast, the 3p lower laser states have populations which correspond to an excitation temperature of 43 eV compared with the neon-like ground state population. The excited states have much lower populations than the electron temperature would suggest because this is a coronal plasma where the rapid radiative decay of the n = 3 states to the neon-like ground state is much faster than collisional depopulation. This is no surprise since the reason these plasmas lase is because they are not in equilibrium.

Under the plasma conditions just mentioned, in the region of peak gain, Fig. 1 shows the radiative and net collisional rates in $nsec^{-1}$, labeled γ^R and γ^C, respectively. To populate the 3d upper laser state, the photoexcitation rate from the ground state due to the radiation field, labeled γ^P, 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 thirty 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 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 farther out of equilibrium and creates the strong gain on the $3d \rightarrow 3p$ lines.

4. Radiation Transfer

To understand the role that radiation trapping of the $n = 3 \rightarrow n = 2$ resonance lines has on the gain of the neon-like argon laser lines we did a series of LASNEX and XRASER calculations for hypothetical plasmas of different thicknesses. We used the same laser pulse as discussed before to illuminate a fixed density target of 0.1 mg per cm^3, which is near the calculated optimum density. We turned off all hydrodynamic motion in the calculation so that we could calculate very thin plasmas without the density changing. We calculated plasmas with thicknesses from 0.1 to 200 microns. The plasmas all reach similar temperatures so the differences are primarily due to the radiation transfer of the neon-like

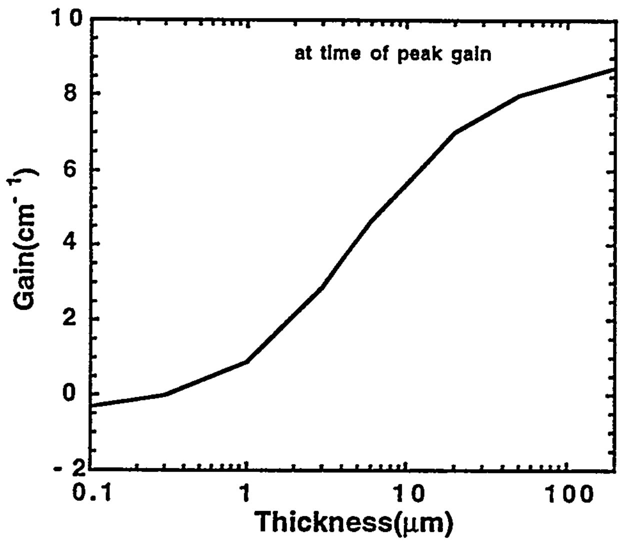

Fig. 3. Gain of the neon-like argon 3d → 3p line at 45.1 nm vs plasma thickness.

resonance lines. The gain peaks at 300 ps before the peak of the laser drive. By looking at the gain in the middle of the plasma we can study the effect of radiation pumping on the gain. One optical depth τ for the pump line corresponds to 1 μm thickness. If we look at the gain of the 3d → 3p line at 45.1 nm versus plasma thickness in Fig. 3, we see that below one optical depth the gain is very small and even goes negative but that in the region of τ from 1 - 10 the gain increases quickly with optical depth and then begins to roll over for $\tau > 10$.

5. Experiments

Recently experiments have been done using an argon gas puff as the laser target to study lasing on the neon-like 3p $^1S_0 \rightarrow$ 3s $^1P_1$ transition at 46.9 nm. This $J = 0 \rightarrow 1$ line has been observed to lase in many low-Z neon-like ions. The surprising result in the argon experiments was that another unidentified possible laser line appeared at 45.1 nm. We believe this line to be the 3d $^1P_1 \rightarrow$ 3p $^1P_1$ transition which is lasing due to the self photo-pumped process described in this work. Both lines completely overshadow the continuum emission. While no gain measurement of the 45.1 nm line has been made, the line is emitted from the same plasma region as the 46.9 nm line and it disappears when shorter targets are used. In recent experiments done with solid sulfur targets illuminated with the prepulse technique at the Asterix laser facility a strong unidentified line was observed at 60.1 nm, very near the strong 3p → 3s neon-like laser line at 60.8 nm. In titanium, experiments done with a picosecond laser drive have observed the normal 3p → 3s neon-like laser line at 32.6 nm as well as a second unidentified line near 30.0 nm. In both cases we believe these unidentified lines at 60.1 and 30.0 nm are the 3d $^1P_1 \rightarrow$ 3p $^1P_1$ transitions in sulfur and titanium, respectively, which are lasing due to the self photo-pumped process described in this work.

6. Nickel-like scheme

In nickel-like ions, the analogous self photo-pumping process is lasing on the 4f → 4d transitions due to photo-pumping by the strong 4f → 3d lines. Figure 4 gives an example using nickel-like molybdenum. The 3.5 nm 4f → 3d pump line drives population into the 4f upper laser state. This lases at 22 nm to the 4d state which is then depopulated by collisional mixing with other 4f and 4p states.

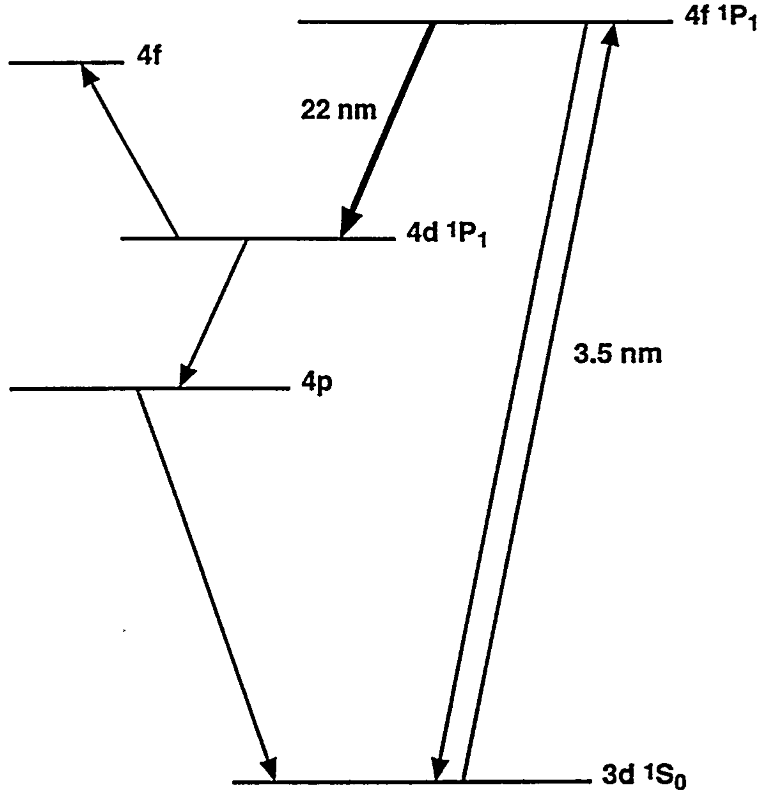

Fig. 4. The photo-pumping mechanism for the 22 nm nickel-like molybdenum laser transition.

7. Conclusions

In conclusion, we propose a self photo-pumped X-ray laser scheme which uses radiation trapping of the strong neon-like 3d $^1P_1 \rightarrow$ 2p $^1S_0$ resonance line to create a strong radiation field which photo-pumps sufficient population from the neon-like ground state to the 3d $^1P_1$ upper laser state to create a population inversion on the 3d $^1P_1 \rightarrow$ 3p $^1P_1$ transition. The 3p lower laser state is depopulated by collisional mixing with nearby 3s and 3d states. This pumping mechanism also enhances the population of the 3p $^1S_0$ state and the gain of the two 3p $\rightarrow$ 3s, $J = 0 \rightarrow 1$ transitions. This generic scheme should work for many low-Z neon-like ions in which the 3d$\rightarrow$2p resonance line can be made sufficiently bright and the right temperatures and densities can be found for lasing. Recent X-ray laser experiments using an argon gas puff target observe lasing on the 3d $^1P_1 \rightarrow$ 3p $^1P_1$ transition at 45.1 nm. This generic scheme should also work in other ionization stages. In nickel-like ions the analogous process would be lasing on the 4f $\rightarrow$ 4d transitions due to photopumping by the strong 4f $\rightarrow$ 3d lines. A more complete description of the argon experiments and theory are given in Refs. [1-3].

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