Proposal for an extreme-ultraviolet selective autoionization laser in Zn III

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A system is proposed whereby Zn atoms that are photoionized by soft x rays from a laser-produced plasma undergo selective super-Coster–Kronig decay leading to inversion and lasing on several XUV Zn III transitions. Calculations indicate that lasing will occur when a moderate-sized (~10-J) 1.06-μm pump laser is used.

It was recently demonstrated that soft x rays from laser plasmas produced by relatively small (<1-J) Nd:YAG lasers are capable of producing large densities of excited atomic species[1,2] and in certain cases of producing inversion and gain on visible and UV transitions.[3,4] In this Letter we propose a system based on this technology to produce population inversion and superfluorescent laser action on three transitions of Zn III with wavelengths of 133.2, 82.9, and 56.8 nm, respectively. X rays from a laser plasma are used to photoionize Zn vapor, producing Zn II $3p^5 3d^{10} 4s^2$ ions. These ions undergo MMM super-Coster–Kronig decay to the $3d^8 4s^2$ configuration of Zn III, which is thereby inverted with respect to the $3d^9 4s$ and $3d^9 4p$ configurations.

The use of Auger processes to create gain in the XUV region was first suggested by McGuire,[5] who proposed that (KLL) transitions in Na II would selectively populate levels in Na V, leading to gain at 410 nm. The required pump power for lasing for this system is large: 300 J in 1 nsec. Bokor *et al.*[6] have demonstrated a visible laser in Ba, which is pumped by a selective autoionization process. Recently, Krolik and Shapiro[7] proposed a scheme similar to McGuire's starting with O IV and using KLL Auger transitions to produce inversions in O VI with gain at 103.5 nm. They predict inversions of about 10%. The Zn system reported here has the following advantages: (1) The use of super-Coster–Kronig transitions leads to large inversions in the lasing species, (2) the initial species is neutral Zi vapor rather than a multiply charged ion, and (3) the laser power required for superfluorescent laser action in the XUV is moderate—about 10 J in 1 nsec. In the remainder of this Letter we discuss in detail the mechanism and necessary conditions for creating the population inversion.

Figures 1 and 2 show the levels and transitions relevant to the proposed scheme. The level positions are taken from the results of Dick.[8] The proposed experimental geometry is that used by Caro and Wang in Ref. 1. An intense 1.06-μm laser is focused through Zn vapor maintained in a heat-pipe oven onto a solid Ta target. The resultant plasma radiates soft x rays with an approximately blackbody distribution and photoionizes the surrounding vapor.

The key concept in this proposal is that $3p$ vacancies created by photoionization undergo rapid super-Coster–Kronig decay into the Zn III $3d^8 4s^2$ configuration, where they preferentially populate the $3d^8 4s^2\ {}^1G_4$ level.[9–12] Nonsuper-Coster–Kronig transitions (i.e., decays to the $3d^9 4s$ and $3d^{10}$ configurations in Zn III) occur with only about 10% probability. Hence the super-Coster–Kronig process tends to leave the ${}^1G_4$ level inverted with respect to levels in the $3d^9 4s$ and $3d^9 4p$ configurations of Zn III. Population of the lower Zn III configurations by other processes (i.e., electron ionization and excitation) will be insignificant if the electron density is made sufficiently small by increasing the distance to the target of the lasing volume or if the pulse is made sufficiently short.

In Fig. 2 we show three systems utilizing the selective super-Coster–Kronig decay into $3d^8 4s^2\ {}^1G_4$. Also

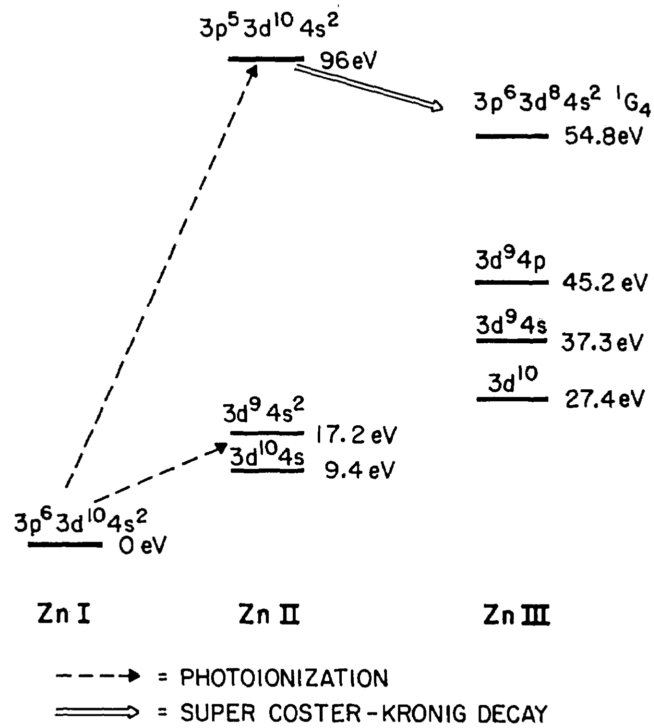

Fig. 1. Population of $3d^8 4s^2\ {}^1G_4$ level by super-Coster–Kronig decay.

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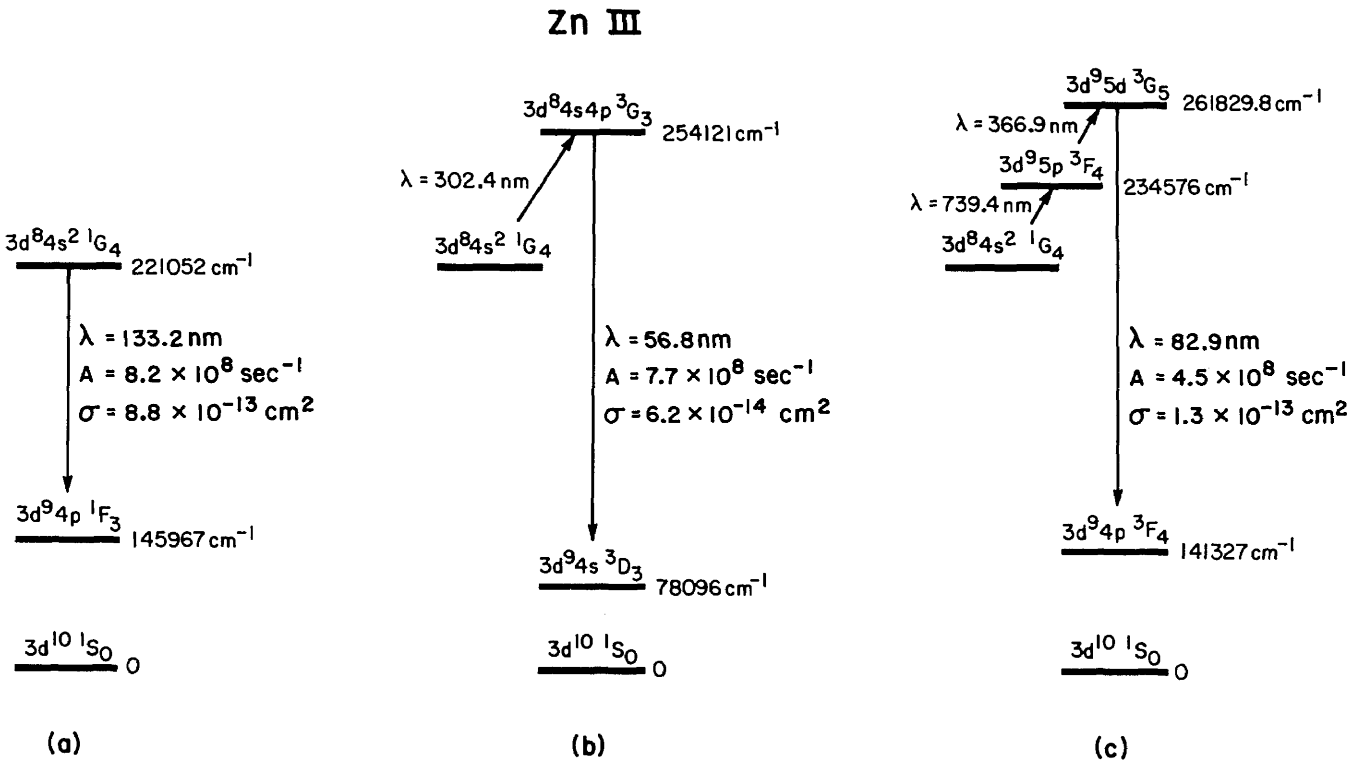

Fig. 2. Energy-level diagrams for three possible laser systems in Zn III.

shown are the Einstein A coefficients and the Doppler-broadened gain cross sections for each of the three laser transitions. These were calculated using the (RCN/RCG) Hartree–Fock code[13] with the effects of configuration interaction included. From the cross sections it is seen that a density–length (Nl) product of 6×10^{14} in the $^1G_4$ level at 221 052 cm^{-1} is sufficient to produce e^{20} gain and superfluorescent laser action in each of the three cases.

Figures 2(b) and 2(c) involve using tunable lasers to transfer the $^1G_4$ population to other Zn III levels. The oscillator strength for the $^1G_4$–$^3G_3$ intercombination line of Fig. 2(b) was calculated to be 7.3×10^{-5}, requiring about 1 mJ/cm^2 of 302.4-nm radiation to transfer the population completely. The oscillator strengths for the two steps of the transfer in Fig. 2(c) are 5×10^{-4} and 0.98, respectively, and require proportionately less laser energy to saturate these transitions.

Another key parameter to be considered is the Zn photoabsorption cross section at the proposed laser wavelengths. These cross sections have been measured by Marr and Austin[14] and are 2×10^{-20} cm^2 and 5×10^{-19} cm^2 at 133.2 and 829 nm, respectively, leading to insignificant loss at typical Zn ground-state densities of 10^{17} cm^{-3} and lengths of ~10 cm. However, the cross section at 56.8 nm was measured by Harrison *et al.*[15] and is 7×10^{-18} cm^2. At these densities this limits the length of the laser column to <1 cm.

The $^1G_4$ Nl product actually obtainable in a laser-plasma-pumped system can be calculated by estimating the number of $3p$ vacancies produced by photoionization and multiplying by the branching ratio for the $^1G_4$ super-Coster–Kronig process. The $3p$ density is determined by the method described in Ref. 2. Assuming a plasma radiation temperature of 50 eV and a conversion efficiency from 1.06-μm laser energy to blackbody radiation of 10%,[16] we calculate that 10 J of 1.06-μm energy focused on a target with an ambient Zn ground-state density of 2×10^{17} cm^{-3} produces a $N_{3p}l$ product of 3.4×10^{15} cm^{-2} at a distance of 11 mm from the target. In this calculation we have used the $3p$ and $3d$ photoionization cross sections calculated by Fliflet and Kelly[17] and the double-photoionization cross-section data of Holland *et al.*[18]

Next we consider the branching ratio for the super-Coster–Kronig process. Chen *et al.*[10] have calculated the Auger rates into each of the possible final terms using LS-coupled single-configuration final-state wave functions. Their results show that 57% of the decays lead to $^1G_4$ final states. The RCN/RCG code gives the composition of the $^1G_4$ level at 221 052 cm^{-1} as $3d^83s^2$ $^1G_4 = -(0.73)3d^84s^2\ ^1G_4 + (0.58)3d^94d\ ^1G_4 - (0.22)$ $3d^95d\ ^3F_4 - (0.29)3d^94d\ ^3G_4$. Hence as an approximation to the effect of configuration interaction we multiply the 57% branching ratio of Chen *et al.* by the fraction $(0.73)^2$ of the $^1G_4$ level that contains the $^1G_4$ basis-state wave function. This leads to a total branching ratio of 30% into the $^1G_4$ level.

The $N(^1G_4)l$ product is then $0.3 \times 3.4 \times 10^{15} = 1.0 \times 10^{15}$ cm^{-2}. Radiative decay of the upper level during a 1-nsec laser pulse reduces this value to 7×10^{14} cm^{-2}. This is sufficient to produce e^{20} gain on all three transitions of Fig. 2.

In the above discussion we have assumed that the incident 1.06-μm laser is focused on the Ta target in a single spot. This in turn leads to an initial photoelectron density of 4×10^{16} cm^{-3}. Depending on recombination rates, inelastic electron collisions and ionization may populate the lower Zn III levels and destroy the inversion. To mitigate this problem the laser may instead be split and focused on the target in several collinear spots, thereby lowering the electron density while maintaining the same gain. For the 56.8-nm laser, a design compromise between maximum allowable electron density and permissible photoionization loss will have to be made.

To summarize, we have outlined a method for exploiting the dominant super-Coster–Kronig decay of $3p$ vacancies in Zn to channel a broad spectrum of laser-plasma-generated x rays into a single upper configuration in Zn III. Sufficient population to achieve superfluorescent lasing on three transitions should be obtainable with a moderate-sized (~10-J) laser.

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