Enhanced x-ray gain through photodepopulation

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Radiation trapping currently creates one of the major limitations on population inversion, gain, and size in x-ray lasers. The resulting increase in lower-level population may be reduced by photodepletion to higher energy levels. A natural energy match between hydrogenic lasing ions of nuclear charge Z, for $n=2$ to 4 or 6 excitation, and $Z/2$ radiating ions provides a scalable system for even-Z elements.

INTRODUCTION

Reaching the next short-wavelength plateau (<50 Å) in laboratory x-ray laser development could likely depend on $\Delta n=1$ transitions, because the successful $\Delta n=0$, $3p \rightarrow 3s$ neonlike ion transition[1] does not readily extrapolate that far, and the inherent multiplicity of the $n=4$ to 4 nickellike transitions limits the achievable gain.[2] For $\Delta n=1$ transitions, hydrogenic ions continue to be very attractive candidates, and there has been particular success[3] with the C^{5+} ion at 182 Å on the $n=3$ to 2 Balmer-α transition. The lasing wavelength for this transition extrapolates as simply Z^{-2} (Z being the nuclear charge), e.g., to 45 Å for Mg^{11+}. However, the size becomes micrometer in scale[4] because of the need to avoid radiative trapping on the $2p$-$1s$ Lyman-α resonance transition.

Electron-collisional recombination has proven to be a most promising pumping method for producing population inversions leading to amplified spontaneous emission in the xuv spectral region, with the gain scaling[4] hydrogenically as $\sim Z^{7.5}$. Maximum pumping is obtained in a high-density plasma consisting of totally stripped ions of the element of laser interest in which the electrons are suddenly cooled, leading to rapid collisional recombination and cascading. When the ion temperature is also low, an additional enhancement of the overall gain (scaling as $T^{-1/2}$) is obtained through reduced Doppler line broadening. Also, for a similar laser wavelength, present $\Delta n=1$ recombination-pumped devices operate at a lower electron density than do the electron-collision-pumped $\Delta n=0$ devices, with the added advantage of lower refraction losses through the amplifying line plasma.

Even with these obvious advantages, measured gain coefficients to date seem to be capped at about 3–6 cm^{-1}. This can be associated with a relative population inversion factor $1-N_2g_3/N_3g_2$ which just marginally exceeds zero, due to collisional mixing and radiative trapping at the high densities required for such high gain.[4,5] Hence, $N_3 \approx N_2(g_3/g_2)$. [Here the upper- and lower-state densities are designated, respectively, by N_3 and N_2 and the statistical weights by $g_n=2n^2$ ($n=2,3$) for the Balmer-α transition.]

Hence, to increase the population inversion and thereby the gain to saturation, to improve the overall efficiency, and to increase the plasma size for eventual multiple-oscillator plus amplifier operation, it is important to decrease the population density N_2.

CONCEPT

The density N_2 can be decreased by transferring $n=2$ electrons to the $n=4$ level through absorption of $n=2$ to 1 Lyman-α photons from a second $Z/2$ hydrogenic ion, where Z is the nuclear charge. This results in photoexcitation to the $n=4$ level in the lasing ion (see Fig. 1). From the Rydberg formula this Z, $Z/2$ is a natural match[6,7] which extrapolates readily for all even-Z elements. Also, a $n=3$ to 1 Lyman-β photon in the $Z/2$ plasma to a somewhat lesser degree can depopulate the $n=2$ level by photoexcitation to the $n=6$ level (shown with a dashed line in Fig. 1), followed by cascade to $n=3$

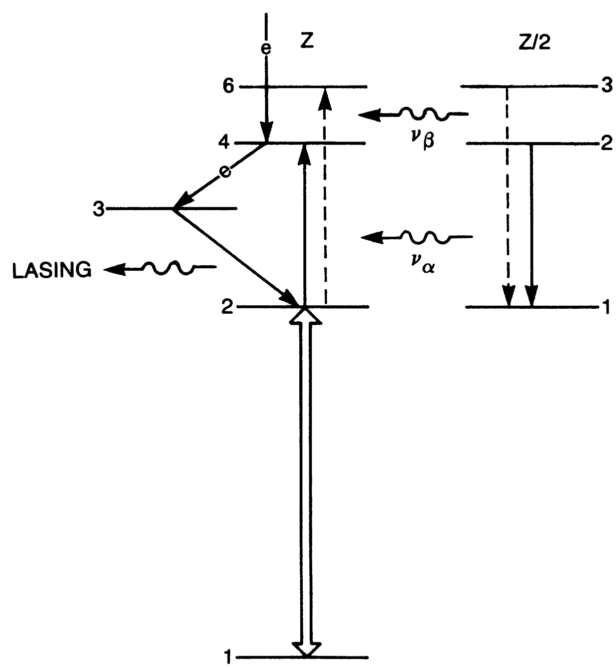

FIG. 1. Hydrogenic energy-level diagrams for $n=3$ to 2 lasing in ions of nuclear charge Z, with $n=2$ depopulated to $n=4$ or 6 by Lyman-α and Lyman-β (dashed) photons, respectively.

for further $n=3$ to 2 inversion and gain. A highly relevant combination is Mg^{11+} $(Z=10)$ lasing on a 3-2 transition at 45 Å with $n=2$ depopulated to $n=4$ and 6 by C^{5+} Lyman-α and Lyman-β emission at 34 and 28 Å, respectively. Such $n=2$ to 4 photoexcitation in Mg^{12+} by C^{5+} Lyman-α emission may have been demonstrated[7] already for pumping fluorescence on a $n=4$ to 3 transition.

is C^{5+} $(Z=6)$ currently lasing at 182 Å and irradiated by Li^{2+} Lyman-α emission at 135 Å. The following analysis is based primarily on the latter, i.e., creating a fully ionized carbon plasma at an electron kinetic temperature $kT\approx 150$ eV, rapidly cooling it to about 20 eV for recombination pumping, and irradiating it with a plasma designed for strong emission on the hydrogenic Li^{2+} Lyman-α line.

A less direct $n=2$ photodepopulation scheme that also could decrease N_2 involves matching only approximately the incident photon energy and the $n=1$ ground-state ionization potential. With sufficient irradiance, such a decrease in N_1 would result in less radiative trapping on the Lyman-α transition and hence a lower density N_2. This could also serve to reionize the lasing ion for additional pumping through the recombination with an overall potential increase in efficiency, an effect already demonstrated,[8] for C^{4+} $2p\rightarrow 1s$ irradiation of lithiumlike Na^{8+} ions. Short of a complete numerical analysis, including nonequilibrium radiative and thermal transport between the two plasmas, some validity can be ascertained by the following considerations.

LITHIUM-CARBON ANALYSIS

The wavelength matches for the Li^{2+}-C^{5+} combination are excellent. Most[9] ($\sim$65%) of the Li^{2+}-ion Lyman-α emission arises from the $J=3/2$ to $1/2$ component at a wavelength[10] of 134.998 Å. For the C^{5+} lasant ion, approximately 63% of the total $n=2$ to 4 absorption occurs on the $2p\rightarrow 4d$ transitions,[11] about 75% (according to statistical weights) of which should occur on the $J=\frac{3}{2}$ to $\frac{5}{2}$ term at a wavelength[10] of 134.990 Å. The main coincidence, therefore, is within 0.008 Å. A convenient figure of merit here is the ratio $\Delta\lambda/\lambda=0.59\times 10^{-4}$, which is much less than a similar ratio of $\Delta\lambda/\lambda\sim 3\times 10^{-4}$ for the Doppler spread[12] of the broader (pumping) line.

To be effective in reducing N_2, the $n=2$ to 4 volumetric photoexcitation pumping rate $N_2 P_{24}$ must at least exceed the $n=3$ to 2 spontaneous decay rate $N_3 A_{32}$ for populating the $n=2$ level (assuming that $\sum_{n>3} N_n A_{n2} \ll N_3 A_{32}$ and that the $n=3$ to 2 lasing is below saturation). Hence,

$$N_2 P_{24} \equiv N_2 N_\nu \sigma_{24} c \geq N_3 A_{32} , \tag{1}$$

where N_ν is the photon density at the lasing ion and σ_{24} is the peak $n=2$ to 4 photoexcitation cross section. The transition probability A_{42} is related by σ_{24} by

$$A_{42}=\frac{8\pi c}{\lambda_{24}^3}\frac{g_2}{g_4}\frac{\Delta\nu}{\nu}\sigma_{24} . \tag{2}$$

For threshold inversion, $N_3/g_3=N_2/g_2$. Also, for Doppler broadening, the relative line width $\Delta\nu/\nu=\Delta\lambda/\lambda$ can again be taken as $\sim 3\times 10^{-4}$, such that Eqs. (1) and (2) give

$$N_\nu=\frac{9\pi}{2}\frac{1}{\lambda_{24}^3}\frac{A_{32}}{A_{42}}\frac{\Delta_\nu}{\nu}$$
$$=9\times 10^{15}\ \text{photons/cm}^3 \tag{3}$$

for the required flux at the lasing ion generated by Lyman-α emission from the $Z/2$ pumping-source ion. (The Lyman-β pumping will reduce this requirement further, but is not included in this simple analysis.)

The quantity N_ν in Eq. (3) may be used to estimate some pumping-plasma characteristics. Assuming a completely congruent plasma mixture, i.e., collection of photons over 4π steradians, the required flux generated by an optically thick Li^{2+} (primed quantities) Lyman-α line of wavelength $\lambda'_{21}=135$ Å $(=\lambda_{24}$ for $C^{5+})$ is given by the blackbody formula:[6]

$$N'_\nu=\frac{4\pi}{\lambda_{24}^3}[\exp(hc/\lambda_{24}kT_B)-1]^{-1}\frac{\Delta\nu}{\nu}\approx N_\nu . \tag{4}$$

Combining Eqs. (3) and (4) for matching line widths leads to the simple relation (independent of wavelength):

$$\exp(hc/\lambda_{24}kT_B)=1+\frac{16}{9}\frac{A_{42}}{A_{32}}=1.3 , \tag{5}$$

for tabulated[11] hydrogenic transition probabilities. This leads to a required brightness temperature of

$$kT_B=4\times 10^4/\lambda_{24}\ \text{eV} , \tag{6}$$

for λ_{24} in Å. For the Li^{2+} Lyman-α line, this becomes

$$kT_B=300\ \text{eV} . \tag{7}$$

Blackbody emission can be assured for an opacity[12]

$$\tau'_{21}=5\times 10^{-17}N'_i\lambda_{24}d(\mu/kT_B)^{1/2}\approx 100 , \tag{8}$$

where $\mu=7$ is the atomic mass number, $\lambda_{24}=135$ Å, and $kT=kT_B$ is in eV. This opacity can be achieved for a $d=1$ mm dimension at an ion density of $N_i\approx 10^{18}$ cm^{-3}.

We can also relate[13] the required photon density N_ν in Eq. (3) to a measurable emitted power W'_P, again starting with congruent plasmas, by[13,14]

$$N_\nu=\frac{W'_P}{4\pi}\frac{\lambda_{24}}{hr^2c^2} . \tag{9}$$

For a characteristic dimension $r=100$ μm (200-μm diam), this gives

$$W'_P\approx 5\ \text{MW} . \tag{10}$$

This could be expected to increase by $\sim$3 times for dual plasmas separated by the same distance.[13,14] That this is in a reasonable range at least for laser-produced plasmas is evidenced by a measured[13] value of 25 MW emitted from a Na^{8+} pumping line in a plasma created by a high-power laser with an irradiance on target of 5×10^{14} W/cm^2.

Such a powerful emission, corresponding to a Li^{2+} plasma temperature of $kT \approx 300$ eV (the brightness temperature for the source), presents the possibility somewhat of overheating (e.g., by thermal conduction) the nearby C^{5+} lasing plasma, which must be cooled to ~ 20 eV for lasing. In this regard, it should be possible to generate initially a homogeneously mixed C^{6+}-Li^{3+} fully ionized plasma at an electron kinetic temperature $kT \approx 300$ eV. This is subsequently cooled to $kT \approx 20$ eV, such that the lower-Z Li^{2+} ions recombine at a lower ($\propto Z^4$) rate to provide the $2p$-$1s$ Lyman-α emission congruent with the carbon ions, which are recombining and lasing much more rapidly. For the sake of argument, suppose the Li^{3+} stripped ions are at such a density as to recombine within the mean C^{5+} Balmer-series decay time (lasing period) of $t_r \sim 100$ ps. For the Lyman-α photon energy of 92 eV, the required 5 MW of congruent power ($=N_i Vhc/\lambda_{42}t_r$) could be produced by an ion density of $N_i = 10^{17}$ cm^{-3} in a laser-heated plasma of 500 μm radius. If operated at 10 times this density to assure a high opacity (see above), the emission would be more than adequate. (This recombination process is most likely the mechanism by which the 25 MW Na^{8+} power was produced.[13]) Hence, because this is a highly nonequilibrium situation, the Li^{2+} Lyman-α emission would not be limited to a brightness corresponding to the 20-eV C^{5+} plasma temperature.

CARBON-MAGNESIUM ANALYSIS

Similar parameters can be derived for the C^{5+}-Mg^{11+} combination (with possible further enhancement by Lyman-β pumping). The wavelength match[10] between the Mg^{11+}-ion $2P_{3/2} \rightarrow 4D_{5/2}$ main absorption transition at 33.733 Å and the $2P_{3/2}$-$1S_{1/2}$ dominant C^{5+} Lyman-α component at 33.734 Å, is 0.001 Å. Also, the figure of merit $\Delta\lambda/\lambda = 0.33 \times 10^{-4}$ is even better (compared to that for Doppler broadening) than was the case for the Li^{2+}-C^{5+} combination above. The carbon-magnesium plasma would have to be heated initially to $kT \approx 600$ eV and then be cooled to $kT \approx 80$ eV for recombination pumping, in analogy to the lithium-carbon scheme.

From Eq. (3), the required photon density N_ν scales as λ_{24}^{-3}, and therefore increases by a factor of $(\frac{135}{34})^3 = 63$, resulting in 7.0×10^{16} photons/cm^3 for Mg^{11+}. From Eq. (5) the blackbody brightness temperature is

$$kT_B = 1.2 \text{ keV} , \tag{11}$$

i.e., about 4 times that for the Li^{2+}-C^{5+} combination. From Eq. (8), an opacity of $\tau'_{21} = 100$ will be obtained at a C^{5+} ion density of 6×10^{18} cm^{-3}, for the same $d = 1$ mm depth.

From Eq. (9), the pump power W_P required scales as N_ν/λ_{24}, so that there is a total λ_{24}^{-4} scaling from Li^{2+} to C^{5+}. This results in an increase by a factor of 250 to 1.2 GW, which is high by present laser-produced plasma standards. It is, however, quite reasonable for large pulsed power devices, where 25 GW of power recently has been measured.[15] However, for nonequilibrium recombination from C^{6+} to C^{5+} in a period t_r reduced by a factor of λ^2, or $\frac{1}{16}$ the time of Li^{3+} to Li^{2+} (i.e., in ~ 6 ps), the ion density $N_i = W_P t_r \lambda_{24}/Vhc$ scales as λ^{-1} and increases only to $N_i \approx 4 \times 10^{17}$ cm^{-3} for C^{6+}.

SUMMARY

In summary, "naturally"-occurring hydrogenic line matches for Z and $Z/2$, $Z/3$ elements promise a reduction of $n = 2$ lower-level population and an associated increase in gain for the $n = 3$ to 2 Balmer-α line. The initial analysis is done for $Z = 6$ and 12. The required Lyman-α pumping-plasma conditions are reasonable for $Z' = Z/2 = 3$ and 6, respectively. The $Z = 6$, $Z' = 3$ example can be readily tested in present recombining C^{6+} to C^{5+} lasers with added lithium [or with lithium carbide (Li_4C_2)].

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