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Model Investigation of a Soft X-ray Photoionisation Laser*

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Abstract

A soft x-ray laser system is proposed in which resonantly excited Mg atoms are rapidly photoionised by soft x-rays from a laser produced plasma, causing inversion and superfluorescent laser action at 24·7 nm in Mg II. Model calculations show that significant gains should occur when a moderately sized (10 J, 200 ps) 1064 nm pump laser is used.

Soft x-rays from laser produced plasmas have been used for several years to photoionise atomic vapours, resulting in high inversion densities between excited ionic levels. With this excitation technique, laser oscillation was first demonstrated in Cd by Silfvast *et al.* (1983). Since then several other elements have been successfully investigated (Silfvast and Wood 1987) and laser radiation in the VUV region has been realised in Xe at 109 nm (Kapteyn *et al.* 1986). The large fluxes of short wavelength radiation (10–70 nm) produced by these plasmas makes this pumping method well suited for soft x-ray laser systems.

Proposed here is a two-step system based on this technique to produce population inversion and lasing on a 3s → 2p transition of Mg II at 24·7 nm. Atomic magnesium vapour is first resonantly excited at 285 nm by a frequency doubled tunable dye laser to the Mg I$[2p^6 3s3p]^1P$ level. A broadband soft x-ray flux (peaked at 80 eV) is then used to photoionise the excited Mg to produce Mg II$[(2p^5 3s)^1P]3p\,^2P_{3/2}$ ions, which are inverted with respect to the Mg II$[2p^6 3p]^2P$ configuration.

The use of the core excited levels in Mg II as a possible source of extreme-ultraviolet (XUV) lasing was first suggested by McGuire and Duguay (1977) and more recently by Pedrotti *et al.* (1985). The former briefly suggested a similar pre-excitation scheme utilising different atomic and ionic levels. However, the scheme suffered the disadvantage of exciting three-quarters of the population at 457 nm via an optically forbidden transition to the Mg I$[3s3p]^3P$ metastable level. The latter suggested using the quasi-metastable Mg II$(2p^5 3s3p)^4S_{3/2}$ level as a storage level for transfer at 160 nm to the $2p^5(3s4s\,^3S)^2P^0_{1/2}$ level for lasing at 23·7 nm. In contrast to this store and transfer system, Hube *et al.* (1988) have demonstrated lasing between 612 and 660 nm produced by innershell photoionisation of resonantly excited K atoms. The Mg system reported here uses the same process of pre-excitation followed by photoionisation to

* Dedicated to Professor Ian McCarthy on the occasion of his sixtieth birthday.

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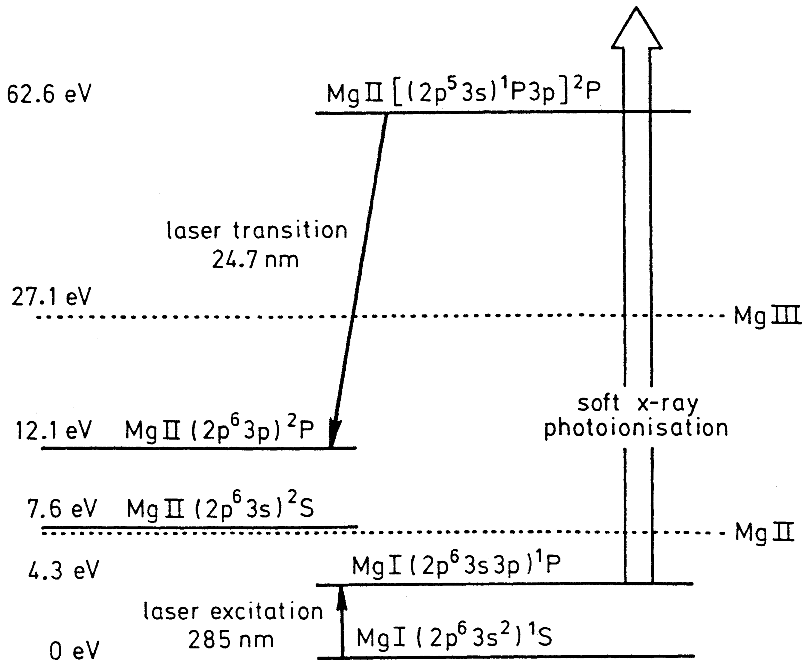

Fig. 1. Magnesium photoionisation laser system.

selectively populate the desired levels. This is believed to be the first plausible and detailed proposal for a short wavelength pre-excited photoionisation laser.

At 80 eV removal of a 2p electron from atomic magnesium is about 50 times more probable than 3s removal. The experimental data of Hausmann *et al.* (1988) give the partial cross sections of $4\cdot5 \times 10^{-18}$ and $8\cdot0 \times 10^{-20}$ cm^2 respectively. Photoionisation from ground state Mg I[$3s^2$]^{1}S in this energy range results mainly in Mg II[$2p^5 3s^2$]^{2}P ions, but these ions autoionise very rapidly to Mg III and any inversion is lost. The key factor in the present scheme is that a main product of photoionisation from excited Mg I[3s3p]^{1}P is the Mg II[($2p^5$3s)^{1}P]$3p^2P_{3/2}$ ion. Pedrotti *et al.* (1985) calculated that this level has an autoionisation rate of only $9\cdot2 \times 10^8$ s^{-1}, compared with a radiative rate of $3\cdot9 \times 10^9$ s^{-1} to the less populated Mg II[$2p^6$3p]^{2}P level. For a typical Doppler-broadened linewidth of $1\cdot8$ cm^{-1}, this gives a relatively large gain cross section of $1\cdot7 \times 10^{-14}$ cm^2. As the lower level has a long decay time relative to that of the upper level, the latter must be pumped at a faster rate than it decays (i.e. before the inversion self-terminates). An energy level diagram for the proposed Mg II laser system is shown in Fig. 1.

A rate equation model, similar to the model described by Caro and Wang (1986), has been used to calculate the gain-length product of the scheme. As described below, it is assumed that half of the Mg I ground state density can be resonantly excited to the Mg I 3s3p^{1}P level. Of course some of this population is itself photionised by the UV excitation pulse (Bradley *et al.* 1975). At the relatively high pressures considered here, however, there is a significant dip (at 285·21 nm) in the ionisation cross section (Zhang *et al.* 1988) due to dimer formation and predissociation to the Mg I $3s3p^3P$ level which cannot be photoionised to the Mg II round state by the UV pulse. Innershell photoionisation from this metastable triplet level still results in relatively high yields of the upper laser level as well as other core excited states of Mg II. Thus the loss from two-photon ionisation can be effectively minimised by tuning the UV pulse exactly to the resonance at 285·21 nm.

Photoionisation from the $3s^2$, $3s3p^1P$ and $3s3p^3P$ states was considered together with a variety of secondary processes which act to diminish or even destroy the inversion. These processes are as follows: (1) autoionisation of the upper laser level, (2) recombination of Mg II states, (3) electron ionisation of Mg I and Mg II states, (4) electron excitation and de-excitation of Mg I and Mg II states, and (5) gain depletion by amplified spontaneous emission (ASE).

The electrons produced via photoionisation are considered to be divided into two classes—a 'hot' class and a 'cold' class. The 'hot' electrons are considered to be monoenergetic (typically around 20 eV). These electrons are cooled by inelastic collisions with atoms or ions and are transferred to the cold electron class. As the thermalisation of the cold electron class by electron–electron collisions is fast compared with the cold electron production, we can assume a Boltzmann distribution with a characteristic temperature less than 1 eV.

Process (1) depopulates the upper laser level at a rate of $9{\cdot}2 \times 10^8$ s^{-1}. Process (2) is a three-body collision ($Mg^+ + 2e^- \rightarrow Mg + e^-$) which has a rate which varies with the square of the cold electron density (hot electrons are not involved). This recombination process reduces the upper laser level population about 5 times faster than the lower laser level population. Processes (3) and (4) describe the effects of electron–atom and electron–ion collisions on the system. The most destructive of these are the 3s electron ionisation of the 3s3p state and the excitation of the Mg II ground state to the Mg II(3s3p) state. Both of these processes further populate the lower laser level and diminish the inversion. Cross sections and oscillator strengths for processes (2)–(4) were taken from experimental data when available (e.g. Brunger *et al.* 1988). These data were supplemented by various theoretical calculations (e.g. Froese-Fischer 1975).

Of all the destructive mechanisms the most important is process (5). In their proposal for a 63·8 nm laser in Cs III, Walker *et al.* (1986) demonstrated the effect of ASE on the magnitude and duration of the gain of their system. This effect was more dramatic for low aspect ratios (i.e. length/width is small). This is because as the population inversion increases, spontaneous emission in directions other than the lasing direction (which is large for small aspect ratio) stimulates even more radiative transitions in random directions, thus reducing the gain without adding to the output of the laser.

Because of the lack of mirrors around 25 nm we modelled the proposed system on the travelling wave geometry described by Sher *et al.* (1987). The pump beam is line-focused onto a grooved target at an angle θ from normal, which increases the gain length (and aspect ratio) by a factor of $1/\cos\theta$ without increasing the pump power requirements. We assume a 10 J 1064 nm pump laser of pulse length 200 ps FWHM focused onto a Ta target in a 3 cm line focus, 1 mm wide at an angle of 68° to normal. This expands the gain length

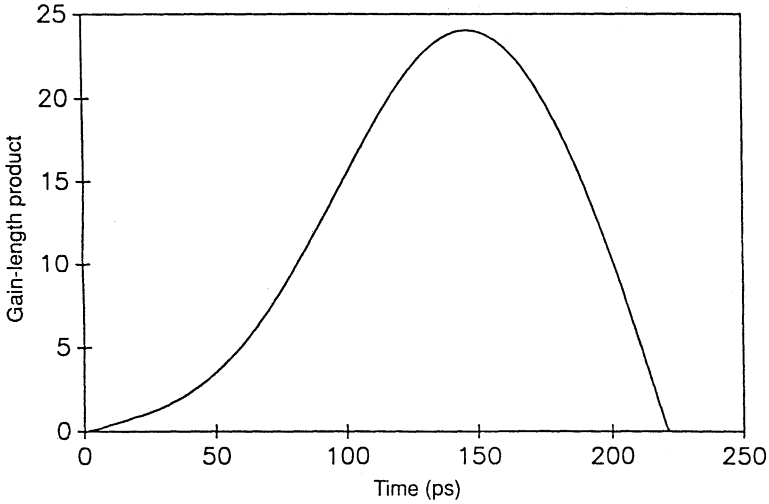

Fig. 2. Gain-length product versus time at a distance of 1 mm from target.

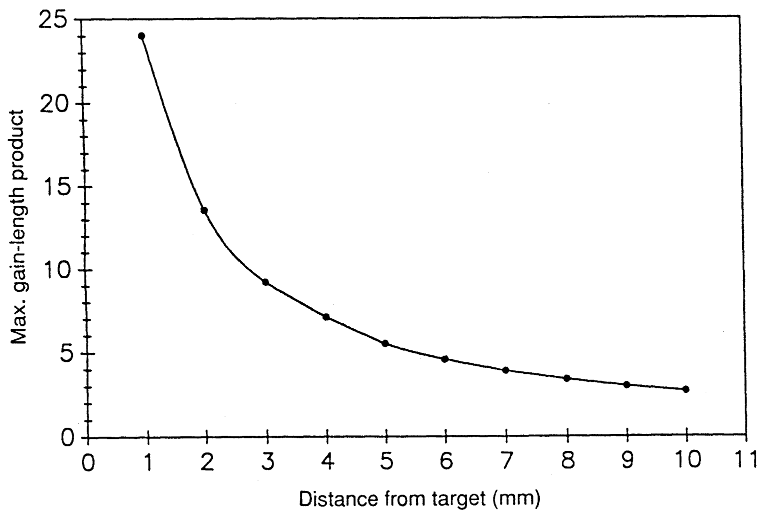

Fig. 3. Maximum gain-length product versus distance of the gain axis from the target for a magnesium pressure of 10 Torr ($=10^{16}$ atoms per cm^3) and pump energy 10 J (200 ps FWHM).

to 8 cm. For a cylindrical volume of 1 mm diameter this implies an aspect ratio of 80. The initial Mg vapour density is taken to be 10^{16} atoms per cm^3. As the transition from the Mg I$(3s^2)^1S$ ground state to the Mg I$(3s3p)^1P$ state is strongly optically allowed ($f_{ij} = 1 \cdot 8$), a strong laser pulse at 285·2 nm should be able to excite approximately half of the Mg vapour to the resonant level. For a 20 cm long cylindrical volume of diameter 3 mm, this implies a pulse energy of 5 mJ. As the 3s3p level spontaneously decays back to the ground state at a rate of $4 \cdot 95 \times 10^8$ s^{-1}, an excitation pulse length of 1 ns and a delay to the pump beam of less than a nanosecond is required. The soft x-ray blackbody temperature of the laser produced plasma is taken to be 18 eV. The conversion efficiency of 1064 nm laser energy to soft x-rays is conservatively assumed to be 5% (Walker *et al.* 1986).

Shown in Fig. 2 is the time dependence of the gain-length product calculated by our model, displaying the rapid self-terminating nature of the lasing transition. The gain axis is taken to be 1 mm from the target, where an aspect ratio of 80 is valid. A relatively large amplification of exp(24) is predicted. Fig. 3 shows the dependence of the maximum gain-length product versus the distance of the gain axis to the target. It can be seen how dramatically the amplification decreases with increased distance from the target.

Ideally a higher Mg vapour density is desirable to maximise x-ray absorption in the active volume, but this exacerbates experimental difficulties related to operating temperatures for thermally generated vapours. Moreover, at higher vapour pressures the transfer of population from the resonant Mg I$(3s3p)^1P$ state to the metastable Mg I$(3s3p)^3P$ state via dimer formation and predissociation would tend to dominate. This would decrease the upper laser level population and enhance photoionisation to a variety of other levels. To achieve the maximum population in the Mg II$[(2p^5 3s)^1P]3p\,^2P_{3/2}$ upper laser level, the soft x-ray pump pulse should occur within a nanosecond of the 287 nm dye laser excitation pulse to minimise such transfer of population to the triplet state. In fact by varying the delay between the excitation and pump pulse it should be possible to vary the core-excited population from the Mg II$[(2p^5 3s)^1P]3p\,^2P_{3/2}$ level to the quartet storage level Mg II$(2p^5 3s3p)^4S_{3/2}$.

To summarise, a method has been described that uses photoionisation of excited magnesium to produce population inversion and gain in Mg II at $24 \cdot 7$ nm. Model calculations show that a 200 ps, 10 J pulse from a 1065 nm Nd:YAG laser should produce significant superfluorescent laser action with a maximum amplification of exp(24).

This proposed scheme will be experimentally investigated by us using the high power laser system at the Australian National University laser facility.

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