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Investigations on soft x-ray lasers with a picosecond-laser-irradiated gas puff target

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Abstract. We present results of experimental studies on transient gain soft x-ray lasers with a picosecond-laser-irradiated gas puff target. The target in a form of an elongated gas sheet is formed by pulsed injection of gas through a slit nozzle using a high-pressure electromagnetic valve developed and characterized at the Institute of Optoelectronics. The x-ray laser experiments were performed at the Lawrence Livermore National Laboratory using the tabletop Compact Multipulse Terawatt (COMET) laser to irradiate argon, krypton or xenon gas puff targets. Soft x-ray lasing in neon-like argon on the *3p-3s* transition at 46.9 nm and the *3d-3p* transition at 45.1 nm have been demonstrated, however, no amplification for nickel-like krypton or xenon was observed. Results of the experiments are presented and discussed.

INTRODUCTION

Efficient laser-driven soft x-ray lasers are strongly required for many applications in science and technology. Substantial advances in the field have been achieved during the last few years using different variants of the prepulse technique and the travelling wave excitation [1-5]. In this technique a solid target is irradiated with two laser pulses. The first pulse creates a large-scale length preformed plasma, and the subsequent pulse heats the plasma to lasing conditions. Strong soft x-ray lasing with neon-like and nickel-like ions has been demonstrated with less than 10 J of laser pumping energy when the second pulse is a picosecond laser pulse from the CPA (chirped-pulse amplification) laser [6-9]. This opens the way for practical table-top soft x-ray lasers.

In this work we present investigations on soft x-ray lasers using a picosecond-laser-irradiated gas puff target instead of a solid. The gas puff target in a form of an elongated gas sheet was formed by pulsed injection of gas from a high-pressure solenoid valve through a slit nozzle. The gas puff valve was developed and characterized at the Institute of Optoelectronics. Gas puff targets have been used to obtain soft x-ray lasers pumped with sub-nanosecond high-energy lasers [10] and pose a number of substantial differences and advantages when compared to solid targets.

A fundamental difference between gas puff and solid targets is that the gas puff provides the gain medium at a density closer to the lasing conditions. The laser-plasma coupling is also much different than with a solid, since the plasma starts below critical density. Moreover, use of a gas puff target instead of a solid target offers the advantage of developing a high-repetition rate x-ray laser with no target debris production. The gas puff target provides better control over the density and minimizes gradients in the plasma.

SOFT X-RAY LASER EXPERIMENTS

The x-ray laser experiments were performed at the Lawrence Livermore National Laboratory using the Compact Multipulse Terawatt (COMET) laser system. Two laser pulses of time duration 0.6 ns and 6 ps with a total energy of 10 J, were focused onto an elongated, sheet-like gas puff target of the maximum length of 0.9 cm. The line focus with length of 1.6 cm was achieved by using a cylindrical lens in combination with an on-axis paraboloid. The target was irradiated using the travelling wave geometry. The soft x-ray spectrometer equipped with a variable-spaced flat-field grating and a CCD camera was used to measure x-ray laser spectra along the axis of the line focus. Additionally, the plasma column was imaged using a x-ray camera with two crossed slits. The details of the experimental setup are given elsewhere [11-12].

Two series of experiments have been carried out. In the first series, performed in January 2000, the collisionally excited transient gain soft x-ray lasers with nickel-like krypton and nickel-like xenon were studied. Although the computer simulations showed high gains for both lasers, no lasing was observed in those experiments. The results of the studies were presented at the 7th X-ray Laser Conference at Saint Malo [13]. The reason for the lack of lasing was not clear, however, one reason may be related to optimizing the correct Kr gas density in the interaction region. In the case of the xenon laser the energy of the pumping laser pulse may not be sufficient for lasing. The x-ray laser with nickel-like xenon ions has been demonstrated recently at the Advanced Photon Research (APR) Center in Japan using the gas puff target created with the same valve but irradiated with higher laser energies [14].

In the second series of experiments performed at Livermore in March 2001 we studied soft x-ray lasing with neon-like argon ions, and strong amplification both on the $3p$-$3s$ transition at 46.9 nm and the $3d$-$3p$ transition at 45.1 nm was demonstrated with gain coefficients of 10.6 cm^{-1} for both lines on a maximum target length of 0.9 cm [15]. The output of both lines was stable and reproducible as a result of optimizing the experimental conditions. Spectral and spatial characteristics of the x-ray laser beams have been measured for various parameters of the gas puff targets and the pumping laser pulses [11, 12]. The beam divergence was measured to be 9 - 12 mrad (FWHM), containing narrow 1.2 – 3.0 mrad (FWHM) features, for the x-ray laser beams [12]. A typical on-axis spectrum from an irradiated gas-puff is shown in Fig. 1(a). Both x-ray

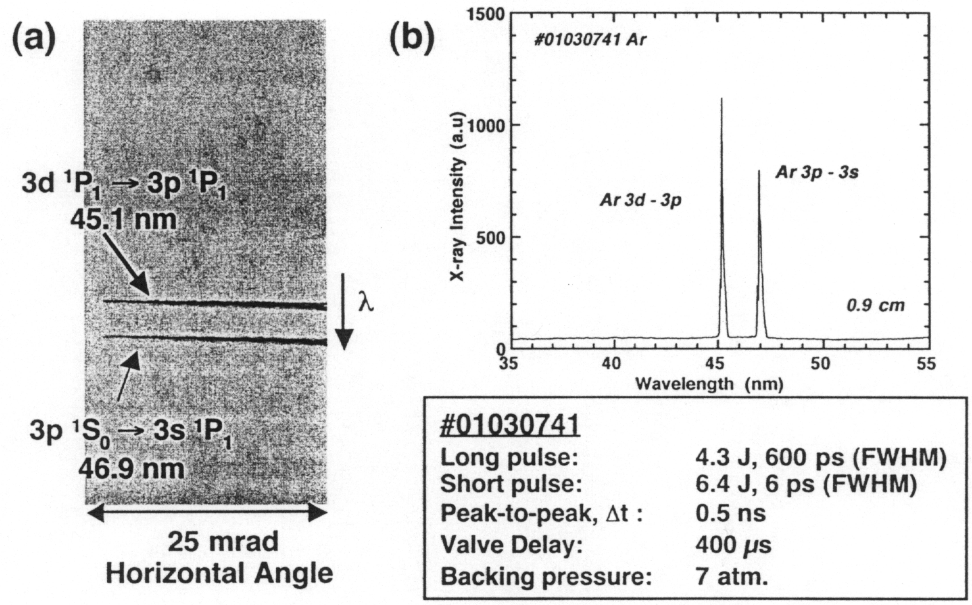

Fig. 1 (a) On-axis spectrum from an Ar gas puff target showing intense x-ray laser lines at 45.1 nm and 46.9 nm. The orthogonal direction to the dispersed axis is the horizontal deflection angle of the x-ray laser lines in the plasma blow-off direction. (b) An intensity lineout through the spectrum (a). Laser and experimental conditions are tabulated.

lines are labeled and the intensity of two x-ray laser lines are many orders of magnitude higher than non-lasing lines. The laser and experimental conditions are tabulated below Fig. 1(b). This was a spectra where the *3d-3p* transition at 45.1 nm was more intense than the *3p-3s* transition at 46.9 nm [12].

A transient gain soft x-ray laser for neon-like argon has been demonstrated also at the APR using the same type of gas puff target irradiated with two picosecond laser pulses of a total energy of 9 J [16]. A higher gain coefficient of 18.7 cm^{-1} and a narrower beam divergence of less than 3.7 mrad was measured for the $3p - 3s$ transition at 46.9 nm with gas puff targets up to 0.45 cm long. No $3d - 3p$ line at 45.1 nm was observed. A possible explanation of the differences between the two experiments can be connected to the larger than expected deflection angle of ~ 26 mrad for the x-ray laser beams presumably due to refraction of the x-rays in a higher density plasma column [12, 15]. Indeed, when the x-ray output measurements for the 0.9 cm long plasma column are neglected, the estimated gain coefficient for the shorter column will be similar for both experiments. This subject has been disscussed in a previous paper [17], however, more precise measurements of the gas density and the plasma density profiles as well as detailed studies of laser gas puff coupling are required to give better insight into the amplification process. The density measurements are planned for the next series of joint experiments at LLNL using x-ray spectroscopy and soft x-ray laser interferometry, in collaboration with Colorado State University. In this experiment we also plan to perform the gain measurements using a gas puff target up to 2 cm long. It is expected to reach the saturated operation for the argon laser.

The problem of the refraction and the gain decreasing for longer plasma columns could be solved by using a gain medium in a form of a plasma channel for waveguiding of the x-ray laser beam during amplification [18]. The possibility of creating a plasma channel in a gas puff target irradiated with a nansosecond laser pulse focused with an axicon, that should be useful for x-ray amplification, was demonstrated a few years ago [19]. The experiments on a transient gain soft x-ray laser produced in a plasma channel formed with an axicon will be performed.

CONCLUSIONS

Experimental studies on transient gain soft x-ray lasers using gas puff targets irradiated with picosecond laser pulses were presented. The x-ray laser experiments were performed at the Lawrence Livermore National Laboratory using the COMET laser to irradiate argon, krypton or xenon gas puff targets formed by pulsed injection of gas through a slit nozzle using a gas puff valve developed at the Institute of Optoelectronics. Amplification in neon-like argon ions was demonstrated, however, without amplification in nickel-like krypton or xenon ions. A strong effect of refraction of x-rays on the gain process was observed.

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