Demonstration of Transient Collisional Excitation X-Ray Lasers in Gases


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Abstract. We have demonstrated a high gain neonlike argon ion x-ray laser using a gas puff target. The elongated x-ray laser plasma column was produced by irradiating the gas puff target with line focused double picosecond laser pulses with a total energy of 9 J in a travelling-wave excitation scheme. Strong lasing was observed and a high gain coefficient of 18.7 cm⁻¹ was measured on the transient collisionally excited 3p¹S₀ - 3s¹P₁ transition for neonlike argon at 46.9 nm with targets up to 0.45-cm long. Preliminary result on the nickellike xenon x-ray laser is also discussed.

I. INTRODUCTION

One of the most promising ways of developing table-top x-ray lasers for applications is a scheme based on transient collisional excitation (TCE). This scheme has the advantage that less than 10 J of laser energy from a table-top laser generating picosecond high-power laser pulses with chirped-pulse amplification (CPA) is sufficient for lasing. The first transient gain x-ray laser was demonstrated at 32.6 nm in neonlike titanium[1]. Saturated operation of transient gain x-ray lasers was demonstrated for both neonlike[2] and nickellike ions[3,4] with low pump energy. This opened the way for a practical table-top soft x-ray laser suitable for various applications.

In this paper, we present a result on transient collisional excitation x-ray lasers in which the line-shaped gain medium is produced by laser irradiation of a gas puff target. The use of a gas puff instead of a solid target offers several advantages. From the viewpoint of practical applications, the gas puff target provides a high repetition rate x-ray laser without production of target debris. In principle, the gas puff also allows better control over the density and minimizes gradients in the plasma if we can precisely characterize the interaction processes. However, it is practically difficult to control the location of gas plasma in space and time[5]. X-ray lasers using a gas puff target were first demonstrated with a 0.5 ns duration, 500 J energy laser pulse by a German-Polish collaboration[6]. In our experiment, we used two 1.5 picosecond laser pulses with a total energy of 9 J to create soft x-ray lasing in neonlike argon gas puff
targets, and a transient high gain of 18.7 cm\(^{-1}\) and a narrow beam divergence of less than 3.7 mrad for the neon-like argon 3p-3s lasing line were successfully achieved. Also the nickel-like xenon lasing line at \(\sim 10\) nm was clearly observed with a combination of a 600 ps prepulse followed by a 1.5 ps driving laser pulse, with a total energy of 22 J.

II. Experimental Setup

The experiment was performed on a CPA hybrid laser at the Advanced Photon Research Center of the Japan Atomic Energy Research Institute[7]. This laser provides up to 20 J of light at 1054 nm in a 1.5 ps pulse. For this work, a prepulse had to be applied before the main pulse, therefore we used the double picosecond pulse as the driving laser pulse for the neonlike argon soft x-ray lasing experiment. The separation time between the double picosecond pulses was set to be about 1.2 ns, and the energy ratio of the first pulse to the second pulse was about 1:6.5. The line focus with a length of 0.55 cm and a width of 20 \(\mu\)m was achieved by using a combination of an off-axis parabolic mirror and a spherical mirror[7]. For a typical total output energy of 9 J, the irradiances in the line focus are of about \(7.0 \times 10^{14}\) W cm\(^{-2}\) for the first pulse and about \(4.7 \times 10^{15}\) W cm\(^{-2}\) for the main laser pulse. Traveling wave geometry was used to irradiate the target by using a stepped mirror technique[7].

The gas puff target was formed using a solenoid valve developed at the Institute of Optoelectronics. It was equipped with a 0.6-cm-long nozzle with a 500-\(\mu\)m-wide slit[8]. Argon and xenon gases were used to form gas puff targets. The laser beam illuminated the gas puff target in the transverse direction with respect to the flow of gas. To achieve a high gain, a high gas density around \(10^{20}\) cm\(^{-3}\) is required. Therefore, the laser line focus position was placed about 150 \(\mu\)m above the slit nozzle output. The gas backing pressure in the valve was set to be 10 bar and the valve time delay between the opening of the valve and the laser pulse was 400 \(\mu\)s. The maximum gas density in the interaction region was roughly estimated to be \(\sim 10^{20}\) cm\(^{-3}\) using the x-ray backlighting method[8]. The maximum plasma column length was set to be

![FIGURE 1. Typical on-axis emission spectra for (a) 0.25- and (b) 0.45-cm-long argon gas puff targets irradiated with a 1.2 J, 1.5 ps pulse followed by a 78.7 J, 1.5 ps pulse showing the strong collisionally excited neonlike argon 3p\(^2\)S\(_3\) – 3s\(^2\)P\(_1\) laser line at 46.9 nm.](image-url)
4.5 mm so that the line focus was overfilling the gas puff target in order to avoid residual absorption of the x-ray laser in the cold gas in the direction of the main detector. For the gain measurement, the length of a plasma column was changed by blocking part of the gas puff from being irradiated by means of a thin silver plate.

The main diagnostic, aligned to the axis of the line focus, was a 1200-line/mm flat-field grating spectrometer with a back-illuminated charge-coupled device (CCD). The spectrometer used a gold-coated spherical mirror collection optic to observe the on-axis x-ray emissions. An additional 2400-line/mm flat-field grating spectrometer was aligned 45° off the axis to monitor the ionization balance of the plasma column.

III. Results and Discussions

Figure 1 presents typical on-axis emission spectra for the laser-irradiated argon gas puff targets with two different plasma column lengths of 0.25 and 0.45 cm. The driving laser pulse with a combination of a ~1.2 J, 1.5 ps prepulse and a ~7.8 J, 1.5 ps main pulse was used to irradiate a target, and the total energy was 9.0 ± 1.0 J. One can clearly see from Fig. 1b that the neonlike argon 3p - 3s laser line at 46.9 nm dominates the spectrum for a gas puff target length of 0.45 cm. The x-ray laser intensity is weak but still visible in the spectrum for the length of 0.25 cm, as shown in Fig. 1a. A very large increase in the x-ray lasing intensity with increasing gas puff target lengths from 0.25 to 0.45 cm strongly indicates a very high gain for the neonlike argon 3p-3s x-ray laser. In our experiment, we did not observe the self-photopumped 3d-3p x-ray laser line at 45.1 nm, which was observed to be very strong in the experiment using a combination of a long 600 ps prepulse followed by a 6 ps driving pulse[9]. A shorter pumping pulse of 1.5 ps used in our experiment might be the reason, and our result is advantageous for possible applications.

The x-ray lasing was very stable and reproducible. Therefore, we performed a gain measurement by moving the thin silver plate to vary the plasma lengths from 0.25 to 0.45 cm. In Fig. 2, we show the intensity versus plasma column length for the neonlike argon 3p - 3s laser line. These data points were obtained under the condition of a total driving laser energy of 9.0 ± 1.0 J. Using the Linford formula[10], we obtained a high gain coefficient of 18.7 ± 1.0 cm⁻¹ for the neonlike argon 3p - 3s, J = 0 - 1 transition lasing. This corresponds to a gain-length product of 8.4 for the 0.45-cm-long plasma column.

From the registered spectral distribution, we could also obtain the angular profile of the x-ray laser line and determine the beam divergence angle.
Figure 3 shows the angular distribution of the neonlike argon 3p - 3s x-ray laser for a gas puff target of 0.45 cm. From Fig. 3, we can estimate the divergence of the x-ray laser beam to be less than 3.7 mrad. However, the angular profile is not so regular and the divergence for the central part is even less than 1 mrad. Tentatively we suppose that this is a result of modes in the amplifier. Also, this value is significantly smaller than that obtained with a combination of a long 600 ps prepulse followed by a 6 ps driving pulse, indicating a larger beam divergence of about 9 - 12 mrad[9]. The small beam divergence achieved in our experiment is mainly due to the 1.5 ps shorter pumping pulse resulting in a more transient gain in the narrower high-density gain region.

In the experiment, we also measured the ionization balance of the line-shaped argon plasma along the direction of 45° off the axis. Figure 4 shows the off-axis spectrum from a 0.45-cm-long gas puff target in the wavelength ranging from 1 nm to 6 nm. In Fig.4, one can clearly observe the very strong neonlike argon 3d-2p resonance lines as well as lines from higher ionization stages. The spectrum strongly indicates a nonequilibrium transient plasma in which the neonlike argon ion abundance may dominate during the ionization phase. Time-resolved spectral measurement is necessary to further clarify these processes.

To extend the scheme to shorter wavelength x-ray lasers, we performed an experiment for the nickellike xenon x-ray laser at ~10 nm with a combination of a 600 ps prepulse followed by a 1.5 ps driving laser pulse, with a total energy of 22 J. A typical on-axis emission spectrum for the laser-irradiated xenon gas puff target was shown in Fig.5. The lasing line at ~10 nm was clearly observed, however we failed to make it stronger for a gain measurement. We think that it is mainly due to a relative low gas density for the xenon x-ray laser, and the next experiment with a higher gas
density over $10^{20} \text{cm}^{-3}$ is planned to obtain a high gain for the nickel-like xenon TCE x-ray laser at 10 nm.

IV. Summary

In summary, we have observed large soft x-ray amplification in neon-like argon ions by irradiation of a gas puff target with two 1.5 ps driving laser pulses with $-9 \text{ J}$ total energy in a traveling-wave geometry. Strong soft x-ray lasing on the transient collisionally excited $3p \, ^1S_0 - 3s \, ^1P_1$ transition for neon-like argon at 46.9 nm was observed. A high gain of 18.7 cm$^{-1}$ and a narrow beam divergence of less than 3.7 mrad were measured on the laser transition for targets up to 0.45 cm long. A weak nickel-like xenon lasing line at $-10 \text{ nm}$ was also observed with a combination of a 600 ps prepulse followed by a 1.5 ps driving laser pulse, with a total energy of 22 J.

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