5.17 Demonstration of a transient high gain nickel-like xenon ion x-ray laser

Peixiang LU, Tetsuya KAWACHI, Maki KISHIMOTO, Kouta SUKEGAWA,
Momoko TANAKA, Noboru HASEGAWA, Masayuki SUZUKI, Renzhong TAI,
Masataka KADO, Yoshihiro OCHI, Masaharu NISHIKINO, Keisuke NAGASHIMA,
Hiroyuki DAIDO, and Yoshiaki KATO, Henryk FIEDOROWICZ*, and Andrzej BARTNIK*
Advanced Photon Research Center, Japan Atomic Energy Research Institute,
8-1 Umemidai Kizu-cho, Souraku-gun, Kyoto 619-0215 Japan
*Institute of Optoelectronics, Kaliskiego 2, 00-908 Warsaw, Poland

We demonstrate a high gain nickel-like xenon ion x-ray laser using a picosecond-laser-irradiated 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 18 J in a travelling-wave excitation scheme. Strong lasing at 9.98 nm was observed, and a high gain coefficient of 17.4 cm^{-1} was measured on the transient collisionally excited $4d-4p$, $J=0-1$ transition for nickel-like xenon ion with target lengths up to 0.45 cm. A weak nickel-like lasing line at a shorter wavelength of 9.64 nm was also observed with a gain coefficient of 5.9 cm^{-1}.

Keywords: X-ray laser, Transient collisional excitation, Gas puff target, Nickel-like xenon ion

1. Introduction

Transient collisional excitation (TCE) has been proved to be the main scheme towards table-top x-ray lasers for applications, and the saturated operation of the lasers was successfully demonstrated for both neon-like[1] and nickel-like[2-3] ions in solid targets with low pump energies. Since a high repetition rate x-ray laser with no target debris production is favorable for x-ray laser applications, transient collisional excitation x-ray lasers using a gas puff target are very attractive. Recently a transient gain was successfully achieved in neon-like argon at a longer wavelength of 46.9 nm.[4-5] In order to extend it to the shorter wavelength region, nickel-like xenon scheme is a good candidate since nickel-like ion x-ray lasers have the advantage of higher quantum efficiency than neon-like schemes operating at similar wavelengths. Experiments on the nickel-like xenon x-ray laser have been carried out at MPQ and LULI using a gas puff target irradiated with 500~600-ps-duration, 400~500-J-energy laser pulses at large-scale laser facilities.[6,7] The nickel-like xenon x-ray lasing line at ~10 nm was observed only in one laser shot at MPQ,[6] and only two very weak lines, which were declared to be lasing lines, were observed at LULI.[7] In this Letter, we present for the first time a high transient gain nickel-like xenon ion x-ray laser driven by double picosecond laser pulses. In the experiment, we used two 3 ps laser pulses with a total energy of 18 J to create soft x-ray lasing in xenon gas puff targets and a high transient gain of 17.4 cm^{-1} for the nickel-like xenon lasing line at 9.98 nm was successfully achieved. This represents the shortest wavelength high gain gas x-ray laser observed to date and demonstrates amplification on the nickel-like analog of the TCE scheme using a gas puff target. Furthermore, a weak nickel-like xenon lasing line at 9.64 nm was also observed with a small transient gain coefficient of 5.9 cm^{-1}.

2. Experimental setup

The experiment was performed on a CPA laser at Japan Atomic Energy Research Institute.[3] This laser provides up to 20 J of light at 1053 nm every 20 minutes with the shortest pulse duration of 400 fs. In the experiment, the driving laser pulse for the soft x-ray lasing experiment consisted of a prepulse and a main pulse both with a duration of 3 ps, separated by 1.2 ns. The energy ratio of the prepulse to the main pulse was about 1 : 8. The line focus is with a length of 0.55 cm and a width of 20 μm.[3] For a typical total output energy of 18 J, the irradiances in the line focus are of about 6.0×10^{14} Wcm^{-2} for the prepulse and about 4.8×10^{15} Wcm^{-2} for the main pulse. Traveling wave geometry with a traveling velocity of 0.98c was used to irradiate the target by using a stepped mirror technique.[3]

The experimental setup is the same as that in Ref.[5]. The gas puff target was formed using a solenoid valve developed and characterized at the Institute of Optoelectronics, Warsaw.[8] It was equipped with a nozzle in a form of a 0.6-cm-long and 500-μm-wide slit. Xenon gas was used to form gas puff targets. The laser line focus was placed at about 80 μm above the slit nozzle output, and the best-focus was set at 100 μm in the front of the nozzle axis. The valve time delay between the opening of the valve and the laser pulse was set to be 410 μs. The gas puff target was characterized using x-ray backlighting method,[8] and the maximum gas density in the interaction region was roughly estimated to be $\sim 5 \times 10^{19}$ cm^{-3} for a backing pressure of 10 bars in the valve. To avoid the residual absorption of the x-ray laser beam in the cold xenon gas surrounding the plasma column, the maximum length of the column was set to be 4.5 mm so that the line focus was longer than the plasma column.

The main diagnostic instrument, 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), which was used to observe on-axis x-ray emissions. An additional 2400-line/mm flat-field grating spectrometer was aligned 45^0 off the axis to monitor the ionization balance of the xenon plasma column.

3. Results and discussions

Figure 1 presents on-axis x-ray emission spectra for the laser-irradiated xenon gas puff targets with two different plasma column lengths of 0.26 and 0.40 cm. From Fig. 1b, one can clearly see a strong lasing line as well as another weak lasing line at a shorter wavelength. The nickel-like xenon 4d – 4p, J=0-1 laser line at 9.98 nm dominates the spectrum for a longer gas puff target length of 0.40 cm. The x-ray laser intensity is weak but still visible in the spectrum for a shorter target length of 0.26 cm, as shown in Fig. 1a. A large increase in the 9.98-nm x-ray lasing intensity with increasing gas puff target lengths from 0.25 to 0.40 cm strongly indicates a high gain for the nickel-like xenon 4d-4p, J=0-1 x-ray laser. To determine the wavelengths of the nickel-like xenon lasing lines, we took a shot to obtain a reference spectrum from a neon gas puff target with a backing pressure of 5 bar. Based on the wavelengths of the nd-2p(n=3-6) lithium-like neon lines, the wavelength for the strong $(3d_{3/2}, 4d_{3/2})_0 - (3d_{5/2}, 4p_{3/2})_1$ lasing line was measured to be 9.98 ±0.02nm, which is just between the calculated values of 10.002 nm[9] and 9.965 nm.[10] The weaker lasing line at the wavelength of

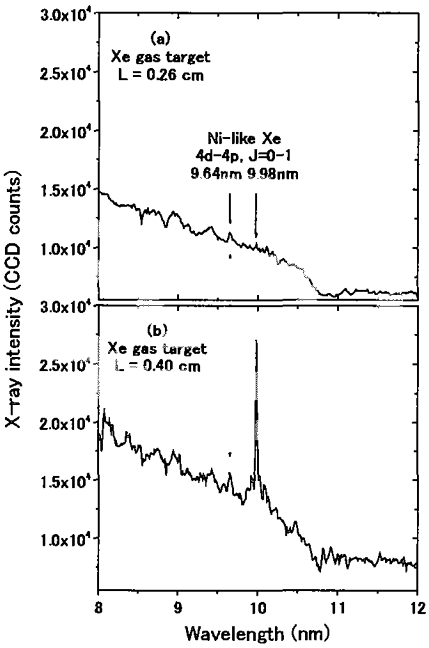

Fig. 1. On-axis x-ray emission spectra for (a) 0.26- and (b) 0.40-cm-long xenon gas puff targets irradiated with a 2 J, 3 ps pulse followed by a 16 J, 3 ps pulse showing the strong collisionally excited nickel-like xenon 4d-4p, J=0-1 lasing line at 9.98 nm as well as the weak lasing line at 9.64 nm. The backing pressure in the gas puff valve is 4 bar.

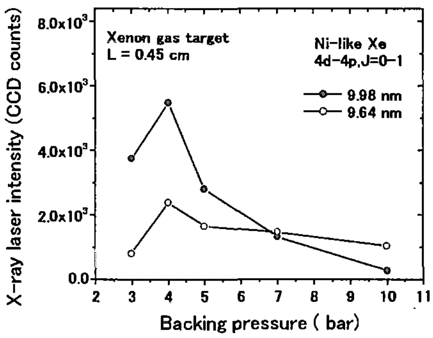

Fig. 2. X-ray lasing intensity versus the backing pressure in the gas puff valve for nickel-like xenon 4d-4p, J=0-1 x-ray lasers at 9.98 nm and 9.64 nm. The length of the plasma column is 0.45 cm. Note that data points for 4 bar are averaged over 6 shots shown in Fig.3.

9.64±0.02 nm may be identified as belonging to the lasing transition of $(3d_{3/2}, 4d_{3/2})_0$ − $(3d_{3/2}, 4p_{1/2})_1$. However, its wavelength is larger than the calculated value of 9.566 nm.[9]

In the experiment, the intensity dependence of x-ray laser lines on the backing pressure in the gas puff valve was measured for the target length of 0.45 cm, as shown in Fig.2. It is shown that both lasing lines have the highest intensity around a backing pressure of 4 bar while the lasing line intensity for both lines decreases with the increased backing pressure, which is discrepant with our prediction that a backing pressure of 10 bar corresponding to an electron density of $\sim 10^{21}$ cm^{-3} is necessary. We suppose that this is a result of the complicated interaction between the laser and the xenon gas, especially for a higher gas density. A high gas density ($>3\times10^{19}$ cm^{-3}) in the case of a backing pressure higher than 6 bar might lead to a strong mismatch between the nickel-like ion abundance and sufficiently high temperature to drive collisional pumping since gas puff targets have very different laser plasma coupling compared to solid targets. The details are not clear yet, however, it seems that such a mismatch limits the operation of our x-ray lasers to the lower electron density region ($\sim 5\times10^{20}$ cm^{-3}) with a relatively low gain. Also in the figure it is shown that the weak lasing line is comparable to the strong one with the increased backing pressure, and even stronger at a backing pressure of 10 bar.

The x-ray lasing was fairly stable and reproducible except for one strongest shot with a target length of 4 mm. Therefore, we performed the gain measurements by moving the thin titanium plate to vary the plasma lengths from 0.26 to 0.45 cm under a backing pressure of 4 bar in the gas valve. Fig.3 shows the intensity versus plasma column length for the nickel-like xenon 4d − 4p, J=0-1 laser lines at 9.64 nm and 9.98 nm. These data points were obtained under the condition of a total driving laser energy of 18.0 ± 2.0 J. Using the Linford formula,[11] we obtained a high gain coefficient of 17.4 ± 2.7 cm^{-1} for the strong nickel-like xenon lasing line at 9.98 nm, and a gain coefficient of 5.9 ± 1.8 cm^{-1} for the weak lasing line

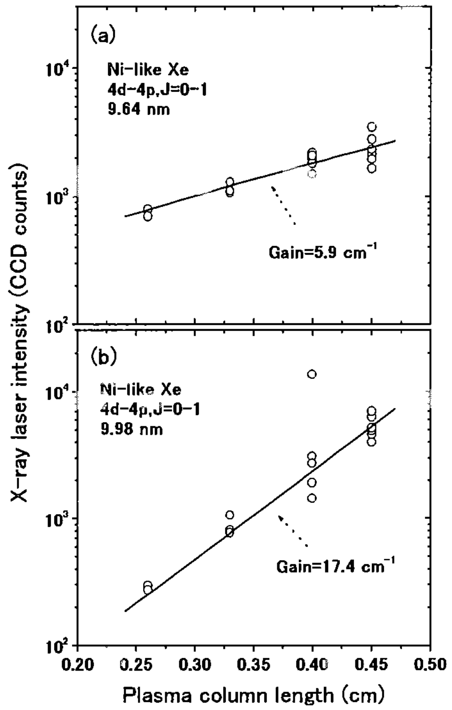

Fig. 3. X-ray laser intensity versus length of the plasma column for nickel-like xenon 4d-4p, J=0-1 x-ray lasers at (a) 9.64nm and (b) 9.98 nm. Fits to the Linford formula[11] are shown by the solid lines. The fitted gain coefficients are 5.9 ± 1.8cm^{-1} for the 9.64-nm line and 17.4 ± 2.7cm^{-1} for the 9.98-nm line, respectively. The exceptional data point for the target length of 4mm is excluded from the gain fitting. The backing pressure in the gas puff valve is 4 bar.

at 9.64 nm. These correspond to gain-length products of 7.8 and 2.6 for the 0.45-cm-long plasma column, respectively. In Fig.3b, we can see that one exceptional data point is far away from the gain curve, and its value is 5~6 times larger than those of other data points for the same target length of 4 mm, which implies that the current x-ray laser did not work mainly under the optimum condition. From the intensity difference between this data point and others for a target length of 4 mm, we can estimate that the gain coefficient for the 9.98-nm lasing line could reach about 22 cm^{-1} if the laser could work under the same conditions as for the best shot.

4. Summary

We have observed for the first time large soft x-ray amplification in nickel-like xenon ions by irradiation of an elongated gas puff target with two 3.0 ps driving laser pulses with ~18 J total energy in a traveling-wave geometry. Soft x-ray lasing on the transient collisionally excited $(3d_{3/2}, 4d_{3/2})_0$ - $(3d_{5/2}, 4p_{3/2})_1$ transition at 9.98 nm and $(3d_{3/2}, 4d_{3/2})_0$ - $(3d_{3/2}, 4p_{1/2})_1$ transition at 9.64 nm for nickel-like xenon ions was observed, gains of 17.4 ± 2.7 cm^{-1} and 5.9 ± 1.8 cm^{-1} were measured on these laser transitions for target lengths up to 0.45 cm.

Acknowledgement

One of the authors (P. Lu) wishes to thank Dr. A. Nagashima for his hospitality.

References

1. M. P. Kalachnikov et al., Phys. Rev. A 57, 4778-4783 (1998).
2. J. Dunn et al., Phys. Rev. Lett. **84,** 4834(2000).
3. T. Kawachi et al., Phys. Rev. A **66**, 033815 (2002).
4. H. Fiedorowicz et al., Opt. Lett. **26,** 1403(2001).
5. P. Lu et al., Jpn. J. Appl. Phys. **41**, L133(2002).
6. H. Fiedorowicz et al., Phys. Rev. Lett. **76,** 415 (1996).
7. D. Ros et al., Opt. Commun. **153**, 368(1998).
8. H. Fiedorowicz et al., Opt. Commun. **163,** 103(1999).
9. J. H. Scofield and B. J. MacGowan, Physica Scripta 46, 361(1992).
10. Y. Li et al., Phys. Rev. A58, R2668(1998).
11. G. J. Linford et al., Appl. Opt. **13**, 379(1974).