Dramatic Enhancement of Optical-Field-Ionization Collisional-Excitation X-Ray Lasing by an Optically Preformed Plasma Waveguide

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Dramatic enhancement of optical-field-ionization collisional-excitation x-ray lasing is achieved by using an optically preformed plasma waveguide. With a 9-mm-long pure krypton plasma waveguide prepared by using the axicon-ignitor-heater scheme, lasing at 32.8 nm is enhanced by 400 folds relative to the case without the plasma waveguide. An output level of 8×10^{10} photon/shot is reached at an energy conversion efficiency of 2×10^{-6}. The same method is used to achieve x-ray lasing in a gas jet for the high-threshold low-gain transition at 46.9 nm in neonlike argon.

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Optical-field-ionization (OFI) collisional-excitation x-ray lasers pumped by femtosecond high-repetition-rate lasers have been shown to be a promising scheme that meets the requirements of practical applications. The first collisionally excited OFI x-ray laser was demonstrated by Lemoff *et al.* for the $5d$-$5p$ transition of Pd-like xenon at 41.8 nm [1]. Later, Sebban *et al.* achieved saturated lasing of the same spectral line with an output of 5×10^9 photon/pulse using 330-mJ pump pulses [2] and strong lasing for the $4d$-$4p$ transition of Ni-like krypton at 32.8 nm with 3×10^9 photon/pulse using 760-mJ pump pulses [3]. All these experiments were done with gas cells. In view of the versatility of gas jets, our group demonstrated nearly saturated x-ray lasing in xenon and krypton clustered gas jets with outputs of 2×10^{10} x-ray photon/pulse and 1×10^9 photon/pulse, respectively [4,5]. For the argon ion, the first Ne-like argon lasing for the $3p$-$3s$ transition at 46.9 nm was demonstrated by using a discharge plasma [6]. Lasing at the same line was also achieved by pumping a gas jet with picosecond laser pulses [7,8]. However, the energy required was as large as a few joules. Owing to its high ionization threshold and much smaller gain coefficient, an OFI collisional-excitation x-ray laser for the 46.9-nm Ar^{8+} lasing has not been realized since it was proposed in 1994 [9].

It was found that the length of gain region for longitudinally pumped gas-target x-ray lasers is severely limited by ionization-induced refraction [2,4]. By using a waveguide to maintain sufficient pump intensity over a long distance, the length of gain region for the x-ray lasing can be increased and the length of the under-ionized absorptive region can be reduced. Butler *et al.* reported the enhancement of OFI Pd-like xenon x-ray lasing at 41.8 nm in a preformed plasma waveguide produced by discharge of a capillary tube filled with Xe/H_2 gas mixture [10]. The lasing intensity with the waveguide was approximately 4 times larger than that achieved with a gas cell. Mocek *et al.* reported the enhancement of Xe^{8+} lasing at 41.8 nm by using a 15-mm-long multimode gas-filled capillary tube [11–13]. Up to 1.5×10^{11} photon/pulse was produced by using a pump energy of 1 J. In addition, Janulewicz *et al.* demonstrated the collisional-excitation x-ray lasing of Ne-like sulfur at 60.8 nm in a preformed plasma waveguide created by ablative capillary discharge and pumped by a picosecond laser pulse [14]. Enhancement of x-ray lasing by a plasma waveguide in a gas jet has not been reported before. In particular, enhancement of the krypton 32.8-nm laser by any type of waveguide has not been achieved before, since the waveguide effect of these two guiding methods was not large enough to overcome the small gain coefficient.

Among all the guiding methods reported, optically preformed plasma waveguide in a gas jet [15–17] is most favorable because it allows (1) guiding of the pump pulse and the lasing x-ray pulse simultaneously, (2) characterization of the underlying process through various diagnostics such as interferometry, and (3) damage-free long-term high-repetition-rate operation for practical applications. Discovering methods to apply an optically preformed plasma waveguide to x-ray lasers has been an ongoing effort since 1995 [18]. In this Letter, we report demonstration of optical-field-ionization collisional-excitation x-ray lasers in an optically preformed plasma waveguide. By using the axicon-ignitor-heater scheme [17] to produce a 9-mm-long plasma waveguide of pure krypton gas, enhancement of Ni-like krypton x-ray lasing at 32.8 nm by a factor of 400 is observed compared to that without the plasma waveguide, resulting in a photon number of 8×10^{10} and an energy conversion efficiency of 2×10^{-6} with a pump pulse of only 235 mJ energy. In addition, taking advantage of the high atom density and large gain length provided by such a plasma waveguide, optical-field-ionization collisional-excitation x-ray lasing for the high-threshold low-gain transition at 46.9 nm in neonlike argon is also demonstrated.

A 10-TW, 45-fs, 810-nm, and 10-Hz Ti:sapphire laser system based on chirped-pulse amplification technique (upgraded from the laser system in Ref. [19]) is used for this experiment. A 235-mJ 45-fs pump pulse is used for preparation of the lasing ionization stage through optical-field ionization and heating of the plasma electrons. It is focused with an off-axis parabolic mirror of 30-cm focal length onto a clustered gas jet. The focal spot size of the pump pulse is 10-μm diameter in full width at half maximum (FWHM) with 85% energy enclosed in a Gaussian-fit profile, corresponding to a vacuum peak intensity of 4×10^{18} W/cm^2. A motorized quarter-wave plate is used to vary the pump polarization. Two laser pulses, referred to as the ignitor and the heater, are used for producing a plasma waveguide. The 45-fs p-polarized ignitor has a maximum energy of 45 mJ and the 80-ps s-polarized heater has a maximum energy of 300 mJ. After combined by a thin-film polarizer, these two pulses with 4-cm diameter in clear aperture propagate collinearly and are then focused by an axicon of 30° base angle to a line focus of >2-cm length in FWHM. The line focus overlaps with the propagation path of the pump pulse in the gas jet. A hole of 5-mm diameter at the center of the axicon allows passage of the pump pulse. To increase the efficiency of waveguide fabrication a convex lens of 40-cm focal length with a hole of 2-cm diameter at the center is located in front of the axicon to concentrate the laser energy in a length (~ 1 cm) matching with that of the gas jet and to optimize the uniformity of longitudinal intensity distribution. Figure 1(h) shows how the laser pulses are combined.

The clustered gas jet used for this experiment is produced from a slit nozzle. The gas jet profile has a flattop region of 8-mm length and a boundary of 500-μm length at both edges along the long axis. A flat-field grazing-incidence x-ray spectrometer, consisting of a 1200-line/mm aperiodically ruled grating and a back-illuminated 16-bit x-ray CCD camera, is used to measure the spectrum and beam divergence of x-ray lasing in the direction of pump laser propagation. Two 0.25-μm-thick aluminum filters are used to block the transmitted pump laser pulse and attenuate x-ray emission. From the known grating reflectivity, filter transmittance, and CCD response, the approximate absolute number of x-ray photons is determined. Mach-Zehnder interferometry with a 45-fs probe pulse passing transversely through the gas jet is used to measure the plasma density distribution. The beam profile of the pump pulse at the exit of the gas jet is measured with a relayed imaging system.

Without the plasma waveguide the maximum x-ray lasing of Ni-like krypton at 32.8 nm is observed at an atom density of 8.0×10^{17} cm^{-3} and a pump focal position of 2.75 mm behind the entrance of the gas jet. The pump pulse is 235 mJ in energy, 45 fs in duration, and circularly polarized. The interferogram taken at 10 ps after the pump pulse has passed through the gas jet is shown in Fig. 1(a). The condition for maximum output is known to be determined by the optimal balance between pump beam convergence and ionization-induced refraction that produces the longest gain region and the shortest x-ray reabsorption region [5,20]. The x-ray lasing spectrum and angular distribution are shown in Fig. 2(a). The number of photons at the 32.8-nm lasing line is 2×10^8 and the x-ray beam divergence is 15 mrad in FWHM. Figure 1(b) shows the interferogram of the plasma taken at the same condition as in Fig. 1(a) except that the krypton atom density is raised to 1.6×10^{19} cm^{-3} and the pump focal position is moved to 500 μm behind the entrance of the gas jet, corresponding to the beginning of the flattop region of the gas profile. Although the increase of ion density should lead to a larger lasing gain, the severe ionization-induced refraction drastically reduces the length of the gain

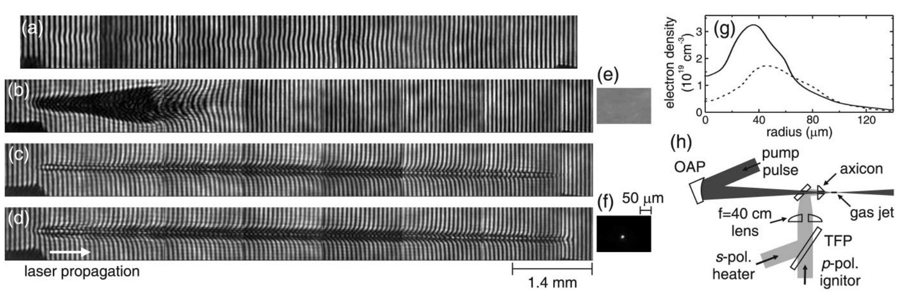

FIG. 1. Interferograms of the plasma taken at 10 ps after the 235-mJ circularly polarized pump pulse has passed through the gas jet. (a) Using only the pump pulse with a focal position at 2.75 mm behind the entrance of the gas jet. Krypton atom density = 8.0×10^{17} cm^{-3}. (b) Using only the pump pulse with a focal position at 500 μm behind the entrance of the gas jet. Krypton atom density = 1.6×10^{19} cm^{-3}. (c) Using only a 45-mJ ignitor pulse and a 225-mJ heater pulse 200 ps after. Krypton atom density = 1.6×10^{19} cm^{-3}. There is no pump pulse and the interferogram is taken at 2.51 ns after the heater pulse. (d) Using the pump pulse guided by the waveguide shown in (c). The beam profiles of the pump pulse at the end of the gas jet for the condition of (b) and (d) are shown in (e) and (f), respectively. (g) shows the radial electron density profiles of the plasma waveguide retrieved from the interferograms (c) (dashed line) and (d) (solid line). (h) shows how the laser pulses are combined.

region, as indicated by the much shorter length of fringe-shifted region compared to (a), and thus no x-ray lasing is observed at this condition.

In order to increase the gain by increasing the atom density and extend the length of the gain region simultaneously, a plasma waveguide is implemented in this experiment. The plasma waveguide is produced by using the axicon-ignitor-heater scheme [17], in which a short intense ignitor pulse provides seed electrons via multiphoton ionization and a subsequent long high-energy heater pulse heats up the plasma through inverse bremsstrahlung heating and further ionizes the gas through collisional ionization. The resultant line-shaped hot dense plasma expands, yielding a reduced on-axis plasma density, and the outgoing plasma ionizes the gas in the encircling outer region through collision. After an adequate delay the plasma electron density in the encircling outer region becomes larger than the on-axis density and thereby a plasma waveguide capable of guiding a laser pulse is produced. Figure 1(c) shows the interferogram of the plasma waveguide at 2.5 ns after the heater for 45-mJ ignitor, 225-mJ heater, 200-ps pulse separation, and 1.6×10^{19}-cm^{-3} krypton atom density. A uniform plasma waveguide of 40-μm diameter and 9-mm length is produced. Figure 1(d) shows the interferogram of the plasma waveguide taken at 10 ps after the pump pulse has passed through the gas jet under the same condition as in Fig. 1(c). The 235-mJ pump pulse is circularly polarized with a focal position of 500 μm behind the entrance of the gas jet and a delay of 2.5 ns after the heater. From the comparison between Figs. 1(b) and 1(d) and also between the corresponding pump beam profiles at the end of the gas jet [Figs. 1(e) and 1(f)], it is evident that the pump pulse is well guided in the plasma waveguide, with a guided beam size of <15 μm in FWHM. Figure 2(b) shows the x-ray lasing spectrum and angular distribution at this condition. With the plasma waveguide the x-ray lasing photon number is dramatically enhanced by a factor of 400 compared to that with only the pump pulse at the optimal condition. The output reaches 8×10^{10} photon/pulse with 10% fluctuation and the x-ray beam divergence is decreased to 5.6 mrad in FWHM with 20% fluctuation. The divergence is close to the ratio of the waveguide diameter to the waveguide length. For this gas jet nozzle the cluster sizes are small, and thus the clusters are easily disintegrated in advance by the ignitor and heater pulses or by the prepulse of the pump pulse [4]. Therefore, the cluster effect of the gas jet does not affect the lasing process.

There is no lasing signal with only the waveguide-forming pulses. The increase of on-axis plasma electron density and the strong x-ray lasing observed when the pump pulse is turned on reveal that the x-ray lasing results from optical-field ionization of the gas driven by the pump laser pulse. Under the same configuration of the pump and waveguide-forming pulses and an argon atom density of

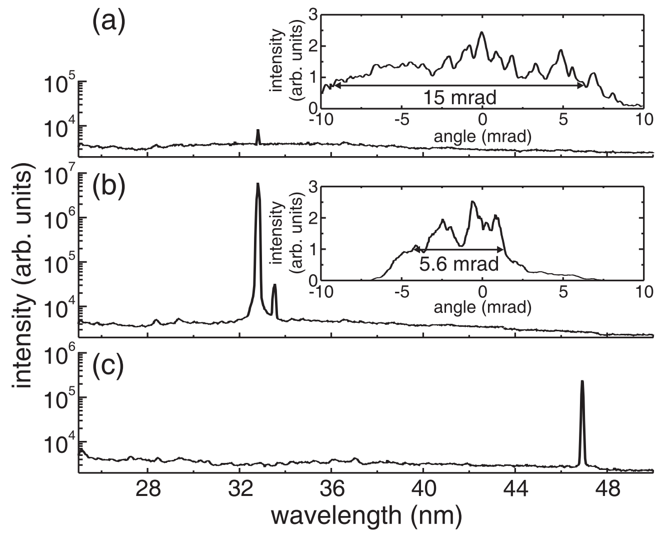

FIG. 2. X-ray emission spectra in the propagation direction of the pump pulse for (a) only a 235-mJ circularly polarized pump pulse with a focal position at 2.75 mm behind the entrance of the gas jet and a krypton atom density of 8.0×10^{17} cm^{-3}, (b) a 235-mJ circularly polarized pump pulse guided in a pure krypton waveguide with an atom density of 1.6×10^{19} cm^{-3}, and (c) a 235-mJ circularly polarized pump pulse guided in a pure argon waveguide with an atom density of 1.9×10^{19} cm^{-3}. For (b) and (c) the ignitor energy is 45 mJ, the heater energy is 225 mJ, the ignitor-heater separation is 200 ps, and the heater-pump delay is 2.5 ns. Insets in (a) and (b) show the corresponding angular distribution of the Ni-like krypton lasing at 32.8 nm.

1.9×10^{19} cm^{-3}, strong lasing at Ar^{8+} 46.9 nm is also achieved, as shown in Fig. 2(c). The output exceeds 1.7×10^9 photon/pulse, even though the laser parameters are not optimized.

It was previously believed that guiding of a pump pulse intense enough for driving an OFI x-ray laser is difficult in a plasma waveguide of pure high-atomic-number (high-Z) gas since OFI leads to a large increase of on-axis electron density and thus may lower the electron density barrier to destroy the guiding condition [10,21]. Therefore, a plasma waveguide of mixed high-Z and hydrogen gases was suggested and also implemented in the capillary discharge plasma waveguide for enhancing an OFI collisional-excitation x-ray laser [10,21]. However, our experiment shows that the action of the pump pulse may actually improve the guiding quality of the plasma waveguide under suitable conditions. Figure 1(g) shows the radial electron density profiles retrieved from the interferograms in Figs. 1(c) and 1(d). At 2.5 ns after the heater the plasma waveguide evolves into one with an on-axis electron density of 4.1×10^{18} cm^{-3} and an electron density barrier (the difference between the peak density at the barrier and the density at the axis) of 1.3×10^{19} cm^{-3}. Right after the pump pulse has passed through the waveguide, both the on-axis electron density and the density in the barrier region increase, resulting in an on-axis electron density of

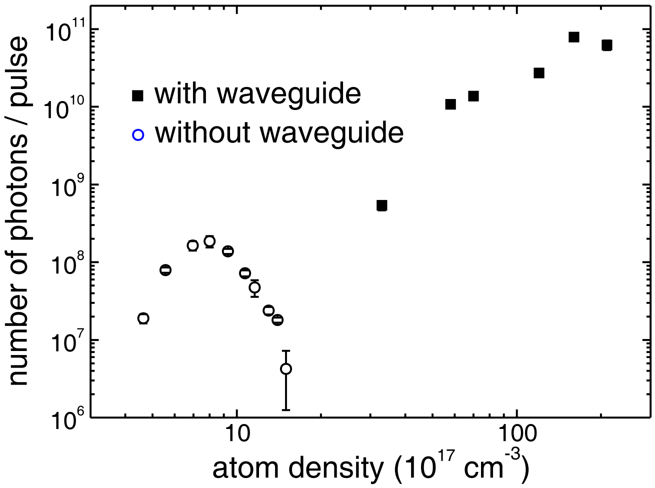

FIG. 3 (color online). Number of photons of Ni-like krypton lasing at 32.8 nm as a function of atom density for the cases with and without a plasma waveguide. The other parameters are the same as those for Fig. 2.

1.3×10^{19} cm^{-3} and an increased electron density barrier of 2.0×10^{19} cm^{-3}. The increase of electron density barrier results from the transverse intensity distribution of the guided pump pulse. Although the average on-axis ionization stage is raised from 2.5 to 8 by the pump pulse, as inferred from Fig. 1(g), the average ionization stage at the barrier position is also increased, for instance, from 1 to 1.9, leading to a larger electron density barrier.

It is interesting to note that another lasing line at around 33.5 nm is also observed in the case of pure krypton plasma waveguide, as shown in Fig. 2(b) with an output of 4.4×10^8 photon/pulse. It is found that the output of the 33.5-nm lasing line is always about 2 orders of magnitude smaller than that of the 32.8-nm lasing line for various atom densities, pump polarizations, pump energies, and heater energies. This seems to indicate that the 33.5-nm lasing line comes from a transition from the same upper level to another satellite lower level close to that of the primary lower level. It may be attributed to the $3d^9 4d\,^1S_0 - 3d^9 4p\,^3D_1$ transition at around 33.4 nm.

The lasing output for Ni-like krypton at 32.8 nm as a function of atom density is shown in Fig. 3 for the cases with and without the plasma waveguide. The other parameters are the same as that for Fig. 2. With only the 235-mJ circularly polarized pump pulse there exists an optimal atom density for maximum lasing output at 8.0×10^{17} cm^{-3} as a result of trade-off between larger gain coefficient and shorter length of gain region caused by ionization-induced refraction with increasing density [2,4]. In contrast, with a plasma waveguide the gain coefficient increases with the on-axis atom density; therefore, the lasing output increases with increasing atom density. The adverse effect caused by ionization-induced refraction is removed by the plasma waveguide. With the presence of the waveguide the lasing output increases exponentially at low densities and then increases roughly linearly with increasing atom density. Such a transition from exponential dependence to roughly linear dependence with increasing atom density indicates that at high densities the amplification reaches the saturation regime.

For the case without a plasma waveguide the optimal pump polarization is found to be circular, and the lasing intensity is reduced drastically with decreasing polarization ellipticity ϵ. For $\epsilon < 0.5$, no lasing is found. In contrast, for the case with a plasma waveguide lasing is achieved with all ϵ, and the output for circularly polarized pump pulses is about 3 times larger than for linearly polarized pump pulses. This again shows the enhancement effect of the plasma waveguide, which enables lasing even for the much less effective linearly polarized pump pulses.

In summary, dramatic enhancement of optical-field-ionization collisional-excitation x-ray lasing for Ni-like krypton at 32.8 nm and Ne-like argon at 46.9 nm by using an optically preformed plasma waveguide is demonstrated. The technique reported in this Letter may be used to enhance various OFI collisional-excitation x-ray lasers to reach the output level for practical applications.

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