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Femtosecond-pulse-driven soft X-ray laser studies using a gas puff target irradiated with a Ti:Sapphire laser

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Preliminary experimental investigations on soft X-ray lasers based on optical field ionization of gases with an ultrashort-pulse terawatt laser system are presented. Both recombination and collisional soft X-ray laser scheme have been studied. An elongated gas puff target formed by pulsed injection of a small amount of gas from a high-pressure electromagnetic valve through a nozzle in a form of a slit was used to create an X-ray laser active medium. The target was irradiated with laser pulses from a 20-fs, 50-mJ Ti:Sapphire (Ti:S) laser system. Soft X-ray spectra from nitrogen, oxygen, and xenon targets are presented and discussed.

1. Introduction

The majority of existing X-ray lasers have been generated using large-scale laser facilities to pump an X-ray laser active medium. Future applications depend on the possibility of developing a short wavelength, highly efficient, low cost, and small size X-ray lasers. Several approaches to improve the performances of current X-ray lasers have been proposed and realized. A comprehensive discussion on this subject can be found in paper [1].

About 10 years ago it was suggested to use high-intensity ultrashort optical pulses to pump soft X-ray lasers [2]. In this method, intense laser light is used to produce strongly nonequilibrium plasmas by optical-field ionization (OFI). With sufficiently high intensity, a population inversion of multiply charged ions can be obtained with large transition energies, which can generate significant gain at soft X-ray wavelength. The opportunity to use this X-ray laser excitation scheme has been opened up with recent advances in ultrashort pulse (< 100 fs) and high-intensity ($> 10^{17}$ Wcm^{-2}) lasers [3]. The X-ray amplification in optical-field ionized plasmas has been reported for both recombination and collisional excitation schemes.

The first OFI soft X-ray laser based on the recombination scheme was demonstrated by NAGATA *et al.* [4] on the Lyman-α transition of H-like Li at 13.5 nm. In this scheme, singly ionized Li plasma were initially prepared by a line focused 20-ns KrF excimer laser pulse from solid target. After a certain delay, a 50-mJ, 500-fs high-power KrF laser was used to drive weakly ionized preformed Li plasma. The laser intensity of about 10^{17} Wcm^{-2} was found to be high enough to produce fully stripped Li ions which started to recombine. Amplified spontaneous emission (ASE) was observed, however, the ionization-induced refraction of the X-ray laser beam associated with the confocal geometry limited the length of the active medium and the gain [5]. It is likely that this problem can be solved by the plasma channel approach to waveguide an X-ray laser beam [6]. A plasma waveguide has been successfully used to improve the performance of the H-like Li soft X-ray laser [7]. The plasma waveguide was formed by ablation and ionization of material from the inner wall of a LiF microcapillary. The use of microcapillary has made it possible to create a lasing medium up to 5 mm long. This X-ray laser was pumped by 50-mJ, 250-fs pulses at the repetition rate of 2-Hz.

In the recombination lasers, the production of cold electrons is the most important issue. It is because this scheme is based on rapid recombination following ionization. Although it was demonstrated that linearly polarized laser beam could produce low-energy rapidly recombining electrons [8], additional cooling mechanisms for OFI plasmas have been proposed. The possibility of rapid cooling of OFI plasmas by metal surfaces placed close to the plasma and soft X-ray lasing to the ground state in C-like O (O III) ions at 37.4 nm was demonstrated experimentally [9]. It was also suggested that doping the lasing medium with an impurity may be a reasonable approach to generating high X-ray gain [10], [11].

The collisionally excited OFI X-ray lasers are based on the tunnelling ionization and subsequent electron collision excitation of ionized atoms (Be-like neon, Ne-like argon, Ni-like krypton, Pd-like xenon). In this case, the intense ($>10^{16}$ Wcm^{-2}) circularly polarized laser light is used to create both the highly ionized species and the hot pumping electrons. To date, Pd-like Xe (Xe IX) at 41.8 nm is the only system in which lasing was experimentally observed [12]. In that experiment, 10-Hz circularly polarized laser pulse with an energy of 70 mJ and a duration of 40 fs was longitudinally focused into a differentially pumped cell containing Xe. The Pd-like Xe (Xe IX) laser was the first soft X-ray laser operating at a 10-Hz repetition rate.

In majority of experiments discussed, an active medium was produced by irradiation of preformed plasmas from solid targets or gas targets in a form of a gas cell. In this paper, we present the results of the experimental investigations in which an X-ray active medium was produced by laser irradiation of an elongated gas puff target [13]. The studies have been performed at the Korean Advanced Institute of Science and Technology (KAIST). A 20-fs, 3 TW Ti:Sapphire laser system was used to irradiate a gas puff target. To produce the target a high-pressure electromagnetic valve equipped with an elongated slit has been developed and characterized at the Institute of Optoelectronics, Military University of Technology, Warsaw, Poland. Soft X-ray spectra obtained from various gases and under different experimental conditions are presented. These investigations are a continuation of the previous studies performed at KAIST using a gas puff target with the circular nozzle [14], [15] and a gas cell [16].

2. Experimental setup

The 20-fs, 3 TW Ti:Sapphire laser system at KAIST is shown in Fig. 1. The system is based on CPA and has been described in detail elsewhere [17]. The Kerr-lens mode-locked Ti:Sapphire oscillator is being pumped by a continuous-wave frequency doubled $Nd:YVO_4$ laser. In the cavity-dumped mode, 17.5-fs pulses at a repetition rate of 167 kHz can be generated and the energy per one pulse is around 30 nJ at a maximum dumping efficiency of about 50%. Increased energy of the seed-beam was proved to relax a gain narrowing problem and to be capable of reducing ASE and prepulses. The prepulse to main pulse ratio of less than 10^{-5} has been measured. The femtosecond pulses from the cavity-dumped oscillator are stretched in time to a pulse length of approximately 200 ps. A single stretched pulse is then selected by a Pockels cell at 10-Hz, efficiently synchronized with the pumping of amplifiers. The selected pulse is injected into a 8-pass preamplifier pumped by the second harmonic of a Q-switched Nd:YAG laser. The output pulses containing energy of 4 mJ are up-collimated to a diameter of 6 mm, and are further amplified in a 5-pass power amplifier. When the power amplifier is pumped by 450 mJ of green (532 nm) light from the Nd:YAG laser, the maximum output energy can reach 130 mJ. After amplification, the laser pulse is recompressed using two parallel (135×135 and 90×90 mm) gold coated holographic gratings with 1200 grooves/mm and the first-order diffraction efficiency of about 90%. The entire compressor system is enclosed in an evacuated chamber. The energy throughput from the compressor is about 45%. A long wavelength injection method [17] was successfully used to obtain a broad amplified spectrum of about 50 nm. The laser is capable of delivering up to 60-mJ, sub-20-fs pulses onto the target at a repetition rate of up to 10 Hz. However, in particular cases, the actual pulse duration may be longer than 20 fs, for example, due to the presence of Faraday rotator. The final polarization of the laser beam is linear and can be easily changed by inserting a mica quarter-wave plate into the beam path after pulse compression.

The laser beam produced with this laser was focused onto a gas puff target using a spherical mirror of 45 cm focal length. A minimum focal spot diameter of about 50 μm was measured, so the estimated maximum laser intensity in the focus could reach $\sim 10^{17}$ Wcm^{-2}. The gas puff valve and the focusing mirror were placed into the compressor chamber. The laser beam was focused along the output slit of the nozzle to be able to form an elongated plasma column ionized as a result of optical field ionization process. The gas puff target has been produced by pulsed injection of a small amount of gas from the valve through the slit nozzle. The width of the slit was 0.5 mm, and the length was 3-, 6-, and 9-mm. The valve was charged with gas at a backing pressure of 10 bar. The gas density in the interaction region could be changed by varying time delay between the

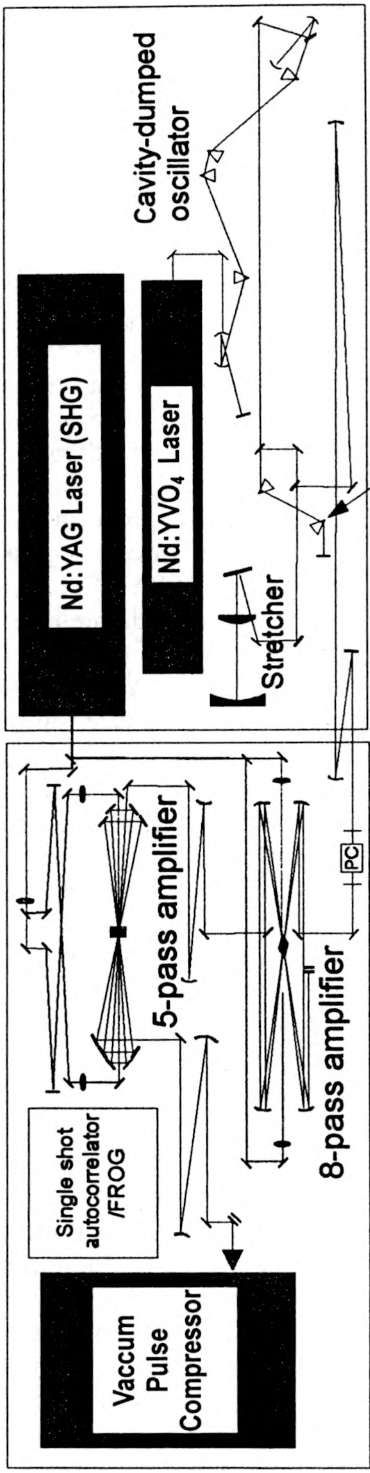

Fig. 1. Schematic of the 20-fs, 3 TW Ti:Sapphire CPA laser system at KAIST.

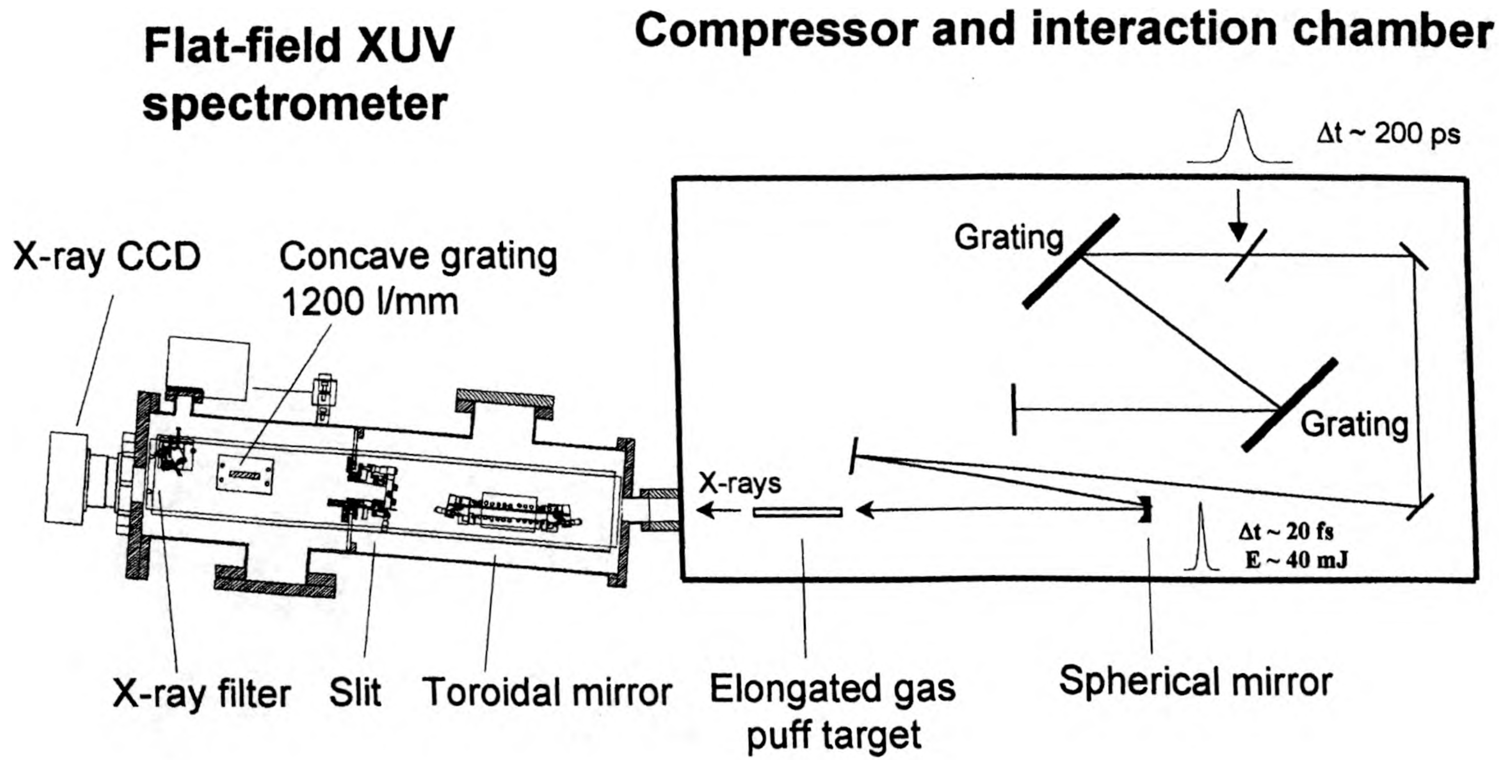

Fig. 2. Schematic view of the experimental setup used for X-ray laser experiments.

triggering pulse driving the valve and the irradiating laser pulse. The gas density profiles were measured using the X-ray backlighting technique.

To measure soft X-ray spectra from an elongated plasma in the longitudinal direction a space-resolved flat-field X-ray spectrograph was used [18]. The spectrograph is composed of a varied line-spacing concave grating (1200 grooves/mm) and a gold-coated toroidal mirror. It is equipped with a backside-illuminated charge-coupled device (CCD) which enables detection of time-integrated spectra. The covered wavelength range is from 4 nm to 50 nm, the spectral resolution is approximately 0.02 nm and 20 nm and the resolving power $R \sim 1000$. However, an X-ray filter (Al or Ti) must be used in front of CCD to block the stray laser light. An Al filter (0.75 or 0.4 μm) transmits X-ray radiation while rejecting visible stray light from the pump laser. Therefore, detectable spectral range becomes from ~18 nm to 50 nm. In the case of 0.2 μm Ti filter, an observable range is from 4 nm to 18 nm. A schematic view of the experimental setup with the compressor chamber, the focusing optics, the gas puff valve, and the X-ray spectrograph is presented in Fig. 2.

3. Experimental results

The experiments of the femtosecond-pulse-driven soft X-ray laser using an elongated gas puff target irradiated with a 20-fs, 3 TW Ti:Sapphire laser pulse have been performed. To be able to study lasing in Li-like N at 24.7 nm [5], in C-like O at 37.4 nm [9], or in Pd-like Xe at 41.8 nm [12], we have used nitrogen, oxygen, and xenon to form the gas puff target, respectively. The paper presents the results of the preliminary measure-

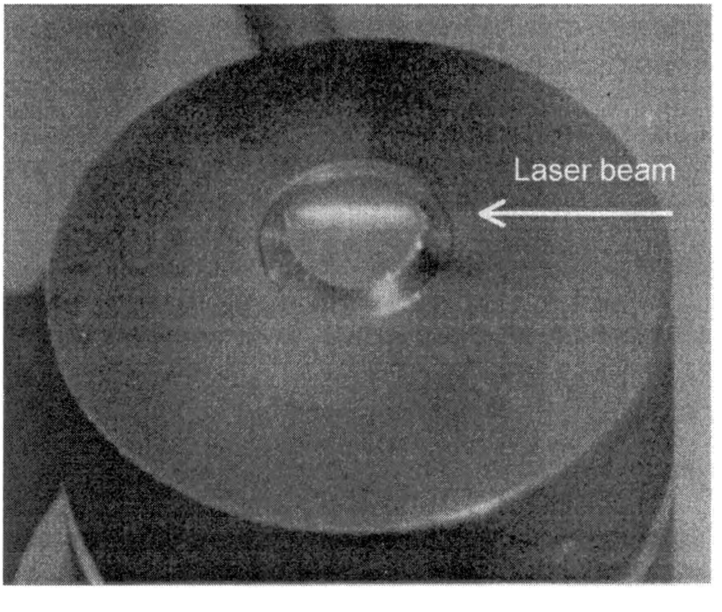

Fig. 3. Plasma column produced as a result of optical-field-ionization of a 6-mm long gas puff target irradiated longitudinally with the femtosecond, high-power laser.

ments performed to test the experimental system. The main issue was production of an elongated gas puff target with repetition rate of 10 Hz and production of a plasma as a result of OFI. In the experiments formation of elongated plasma columns was demonstrated for these gases.

Figure 3 presents an example of the plasma column produced as a result of laser irradiation of a xenon gas puff target produced with the 6-mm long slit nozzle. The plasma column emits intense visible light. The laser beam coming from the right was focused along the slit. The focal spot was placed on the right edge of the nozzle and about 200 μm above the slit. The plasma column depends strongly on the gas density in the terget controlled by changing the time delay between the laser pulse and the trigger pulse driving the valve. For low densities of gas (short time delay) the length of the plasma column corresponded to the length of the nozzle slit. In this case the plasma column was highly uniform, however, emission in the visible range was relatively weak. For higher gas densities (longer time delay) the plasma column became shorther, and the scattering of laser light was clearly seen.

The soft X-ray spectra from OFI plasmas were measured in the longitudinal irradiation geometry. Typical spectra for the 6-mm long nitrogen, oxygen and xenon gas puff targets are presented in Fig. 4**a** – **c**, respectively. The spectra were obtained in 500 laser shots. The predicted lasing lines at $2p-3d$ transitions in Li-like N (N V) and $2p^2-2p3s$ transitions in C-like O (O III) are clearly seen, however, no amplification was observed. For xenon target we have not registered lasing line at $6p-5d$ transitions in Pd-like Xe (Xe IX). These preliminary results show that the parameters of the plasma column are not appropriate for gain. However, the results obtained do not allow us to formulate final conclusions, a few points should be still considered. The measured spectra strongly depend on the time delay. For longer time delays the intensity of the observed lasing lines was depressed and strong emission from harmonics was registered. Probably, this is connected with the smooth density gradients in the gas puff target for the longer time delay, which cause arising

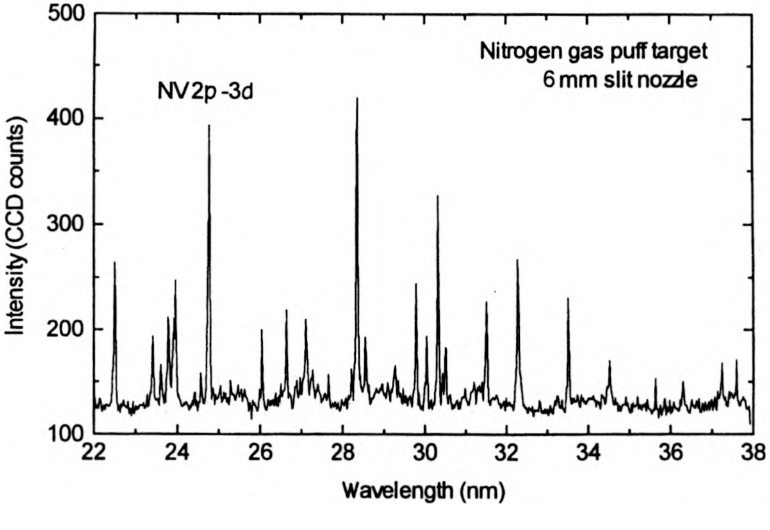

Fig. 4**a**

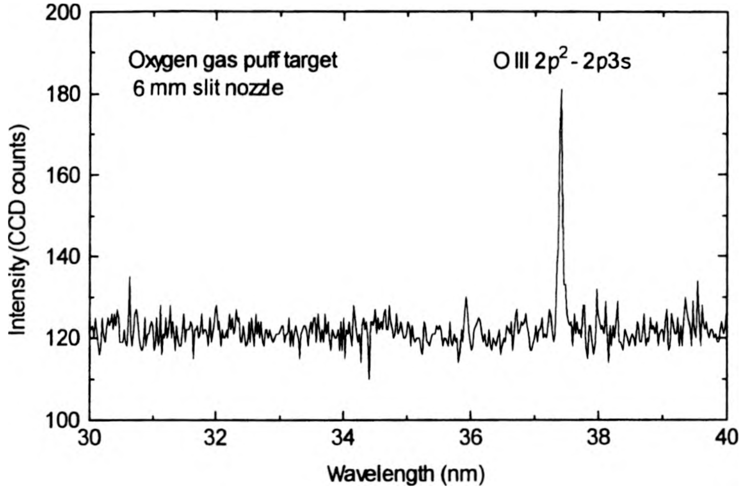

Fig. 4b

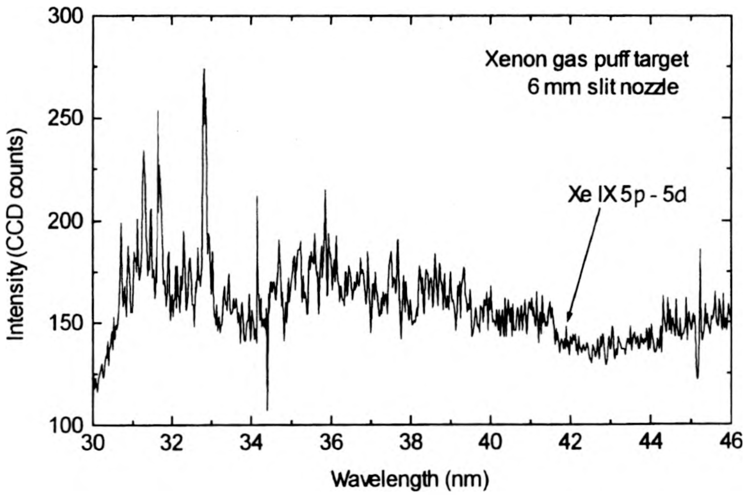

Fig. 4c

Fig. 4. Axial spectra from a nitrogen (a), oxygen (b), and xenon (c) plasma produced by the longitudinal irradiation of an elongated gas puff target with a femtosecond laser pulse (26 fs, 50 mJ, 500 shots).

of a relatively thick, low-density gas layer, where the laser energy is being dissipated. Because of this effect we were not able to irradiate gas at higher densities with high laser intensities. The obtained spectra are similar to those obtained from a gas cell irradiated under the same conditions at the gas pressure being less than 10 torr [16]. In the case of xenon the lasing line seems to be attenuated because of a strong absorption of soft X-rays in the same cold gas surrounding the plasma column. The possible solution would be application of the recently proposed double stream gas puff target approach [19] to form a target for X-ray laser experiments.

4. Summary

Optical-field-ionized X-ray lasers appear to be a promising solution for achieving low-cost tabletop soft X-ray lasers. Lasing for OFI plasmas has been demonstrated for both recombination and collisional excitation schemes. In the experiments preformed plasmas from a solid target or gas have been irradiated with ultra-short, high-power laser pulses.

Investigations on the OFI soft X-ray lasers using an elongated gas puff target irradiated with a 20-fs 3 TW Ti:Sapphire laser were performed. A specially developed electromagnetic valve to produce the gas puff targets with length up to 9 mm has been tested and formation of plasma columns has been demonstrated for the confocal geometry of irradiation. Preliminary measurements of soft X-ray axial spectra for nitrogen, oxygen, and xenon gas puff targets were performed, however, no gain was observed. This is likely connected with the fact of the gas density in the interaction region being too low. High density targets produced using longer time delay between the opening of the valve and the laser pulse irradiating the target are surrounded by a relatively thick low density gas layer that prevents irradiation at appropriate laser intensities. Systematic investigations of this problem, plasma characterization studies, and soft X-ray axial spectra measurements for the optimized gas puff targets are planned. The aim of these studies is to develop an efficient, small size soft X-ray laser pumped with a tabletop femtosecond laser.

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