Soft-X-Ray Amplification of the Lyman-α Transition by Optical-Field-Induced Ionization

Yutaka Nagata,* Katsumi Midorikawa, Shoich Kubodera, Minoru Obara,* Hideo Tashiro, and Koichi Toyoda

The Institute of Physical and Chemical Research (RIKEN) Wako-shi, Saitama 351-01, Japan

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We report the first observation of amplification of spontaneous emission on the Lyman-α transition of hydrogenlike lithium ions by optical-field-induced ionization. Using a subpicosecond KrF laser (0.5 ps, 50 mJ) focused at 10^{17} W/cm^2, singly ionized lithium ions have been further ionized to fully stripped states, resulting in the population inversion with respect to the ground state of the hydrogenic ions. A small signal gain coefficient of 20 cm^{-1} was obtained.

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Recent research in x-ray lasers has focused on the development of more efficient and shorter wavelength lasers which can be pumped by a compact driver. Present x-ray layers [1,2] require large scale and very expensive drivers to heat a plasma medium to a desired ionization state by collisional excitation. Recently, Burnett and co-workers [3,4], Amendt, Eder, and Wilks [5], and Eder, Amendt, and Wilks [6] have proposed a new scheme for an x-ray laser based on an optical-field-induced ionization (OFI). In this scheme, an ultrashort high-intensity laser produces a plasma consisting of fully stripped ions and cold free electrons on a time scale much shorter than the recombination time. In such a plasma, a rapid recombination cascade of the electrons could lead to a population inversion because of a sufficiently low electron temperature of the plasma. X-ray lasing by OFI, however, has not yet been demonstrated.

The use of OFI for the production of an x-ray laser plasma medium introduces some favorable characteristics. First, it is possible to produce population inversions with respect to the ground state of an ion [7,8], leading to a transition to much shorter wavelength compared to relevant transitions. The transition between $n=2$ and 1 in H-like ions has a photon energy 5 times as large as the transition between $n=3$ and 2 state. Second, the use of ultrashort pulses requires a lower pump energy, compared with conventional x-ray laser schemes. The recent progress in the technology of ultrashort laser pulses would make it possible to realize table top laser drivers for OFI x-ray lasers.

This Letter reports the first observation of the amplification of spontaneous emission on the Lyman-α transition (13.5 nm) in H-like Li ions, using a novel optical-field-induced ionization scheme. A very large small-signal gain coefficient of 20 cm^{-1} was obtained from the exponential growth of the 13.5 nm line intensity against the linear increase of the gain length. The anisotropy of the amplified spontaneous emission was also observed by comparing with the relative intensities along on-axis and off-axis directions.

Our method described in this Letter is a unique modification of the original OFI scheme proposed previously [3–6]. In our scheme, singly ionized lithium ions which are initially prepared by a nanosecond KrF excimer laser are further ionized to a fully stripped state by a subpicosecond high-intensity KrF laser. This modified scheme provides some advantages for the production of cold electrons and for pump beam focusing.

Figure 1 shows the experimental arrangement. Two KrF excimer lasers were used; a 20-ns KrF laser was for the preparation of a singly ionized Li plasma, while a subpicosecond KrF laser produced fully stripped Li ions by optical-field-induced ionization. Both lasers were operated at 3 Hz.

By using a combination of two cylindrical lenses, a 20-ns KrF laser pulse was line focused onto a solid Li target in a vacuum chamber at an intensity of 10^9 W/cm^2. This intensity was optimized to create a singly ionized Li plasma dominantly. We estimated an electron temperature of 1.5 eV at this laser intensity by extrapolating data described in Ref. [9]. At this temperature, singly ionized lithium ions exist dominantly in a plasma column [10].

After a certain delay with respect to a 20-ns KrF laser pulse, a 50-mJ, 500-fs high-power KrF laser was focused into a singly ionized Li plasma column at 0.5 mm above the target. With a $f=300$ mm achromatic lens, the focused spot size and the confocal length were measured to be approximately 10 μm and 2 mm, respectively. A maximum focused intensity was thus calculated to be 10^{17} W/cm^2. This estimated intensity is high enough to produce fully stripped Li ions [11–13].

Emission from a Li plasma after subpicosecond KrF laser irradiation was observed by using two spectrographs with a multichannel detector. In the wavelength range between 12 and 30 nm, a flat-field grazing-incidence XUV spectrograph with a varied-spacing concave grating (1200 lines/mm) was employed. This spectrograph had a spectral resolution of 0.07 nm at 13.5 nm.

In order to observe the Balmer-α transition in H-like Li ions (72.9 nm), we used a flat-field normal-incident XUV spectrograph equipped with a varied-spacing concave grating blazed at 60 nm (1200 lines/mm), which covered the spectral range between 30 and 120 nm. A thin film filter made of either a carbon alloy for the Lyman-α line or Al/Si for the Balmer-α line was placed behind an entrance slit of the spectrograph to eliminate

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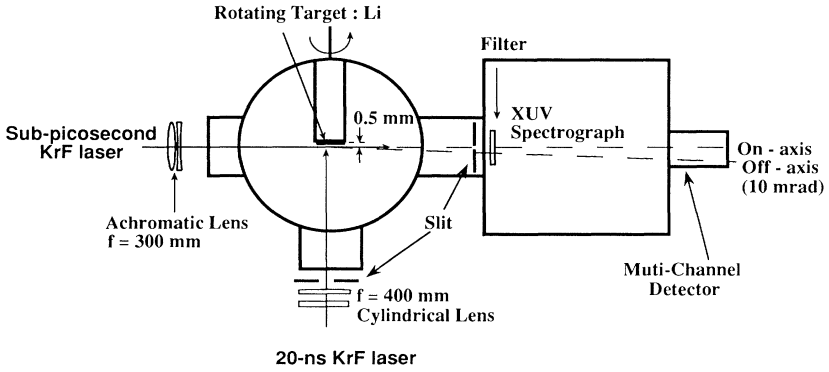

FIG. 1. Schematic diagram of the experimental setup.

scattered light of the subpicosecond KrF laser.

We first optimized a delay time between the nanosecond and subpicosecond KrF laser pulses by monitoring the time-integrated spectral intensity at 13.5 nm. Figure 2 shows the 13.5 nm line intensity as a function of the delay time between the nanosecond and subpicosecond KrF laser pulses. When the delay was less than 30 ns, the 13.5 nm line disappeared. The 13.5 nm line intensity began to increase from 400 ns and reached its maximum at 700 ns. After that, the intensity decreased with an increase of the delay time.

The maximum energy of the 13.5 nm line was larger than the seventeenth-order harmonic energy of the KrF laser (14.6 nm) by 6 orders of magnitude and comparable with the third-order harmonic energy. The harmonic experiments were done with a similar setup and reported in detail elsewhere [10,14]. Emissions due to high-order harmonics of the subpicosecond KrF laser were observed at a delay around 100 ns.

In order to investigate the Balmer-α transition (72.9 nm) in H-like Li ions, we employed a normal-incidence spectrograph. However, no emission was observed under the optimized condition for the Lyman-α transition at 13.5 nm. This is presumably due to a faster collisional relaxation rate of the 3–2 transition compared with the radiative lifetime of it under the present experimental conditions. In addition to the low intensity due to its small photon energy and low transition probability, low transmission of the filter employed (less than a few percent at 72.9 nm) also made it difficult to observe the signal.

A measured electron density as a function of delay time between the nanosecond and subpicosecond KrF laser pulses is shown in Fig. 3. The electron density was estimated from the series limit (Inglis-Teller limit) of the observed He-like Li spectrum. When a delay was set at 700 ns where the Lyman-α line intensity became maximum, an electron density of 2×10^{17} cm^{-3} was obtained. This low plasma density suitably matches to the laser pulse width to minimize the residual electron energy by the above threshold ionization heating [11,15]. The electron temperature was also estimated to be less than 1 eV from the slope of a He-like Li continuum. Under the electron temperature and density, the fully stripped Li ions should commence a rapid three-body recombination [16].

Along an optical axis of a subpicosecond KrF laser, time-integrated spectra from a Li plasma with various

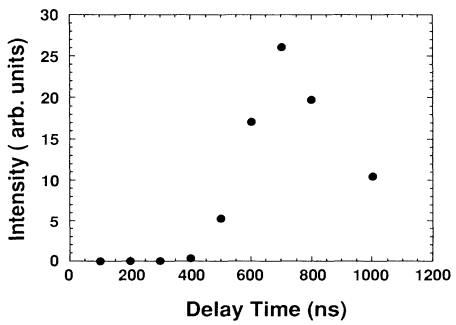

FIG. 2. Time-integrated intensity of the 13.5-nm Lyman-α transition of H-like Li ions as a function of a delay time between nanosecond and subpicosecond KrF laser pulses.

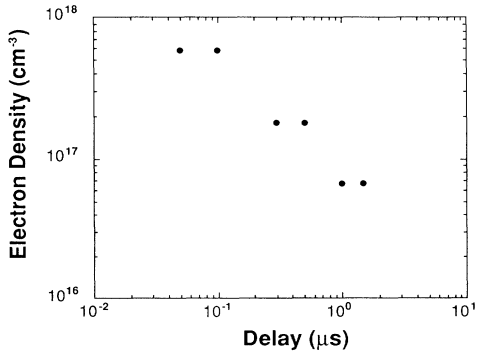

FIG. 3. Measured electron density as a function of a delay time between nanosecond and subpicosecond KrF laser pulses.

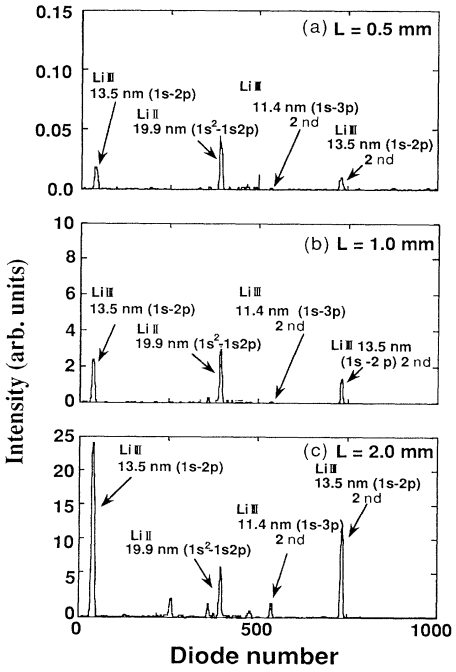

FIG. 4. On-axis spectra from Li plasma subjected to subpicosecond KrF laser pulses under various plasma lengths: (a) 0.5 mm, (b) 1.0 mm, and (c) 2.0 mm.

plasma lengths are shown in Fig. 4. Note that the intensity scales of three spectra are comparable. The Lyman-α line intensity at 13.5 nm increased nonlinearly with an increase of plasma length, while the $n=2$–1 line (19.9 nm) intensity of He-like Li ions increased linearly with respect to the plasma length. It should be noted that the $n=3$–1 line in H-like Li ions (11.4 nm), which was observed as a second-order diffraction light, and the $n=3$–2 line in Li-like oxygen (17.4 nm) showed a nonlinear growth, suggesting the appearance of a gain. Oxygen was probably contained in a lithium target as an OH base. A detailed plasma kinetics model to describe the observed transition strengths will be discussed elsewhere [17].

Figure 5 shows the 13.5- and 19.9-nm line intensities as a function of a plasma length. The plasma length was changed by masking the nanosecond KrF laser pulse as depicted in Fig. 1. Uncertainty of the plasma length due to its expansion was estimated in the figure as error bars, based on the $\cos^2\phi$ distribution which was observed by Dinger, Rohr, and Weber [18], where the focused laser intensity is similar to ours. The 13.5-nm line of the H-like Li increased exponentially, while the 19.9-nm line of the He-like Li increased linearly with respect to the plasma length. In order to determine the gain coefficient g for the 13.5-nm line, the data were fitted by an equation [19], $I=[\exp(gl)-1]^{3/2}/[gl\exp(gl)]^{1/2}$, which describes the frequency-integrated relation between the output intensity I and the plasma length l. A small-signal gain

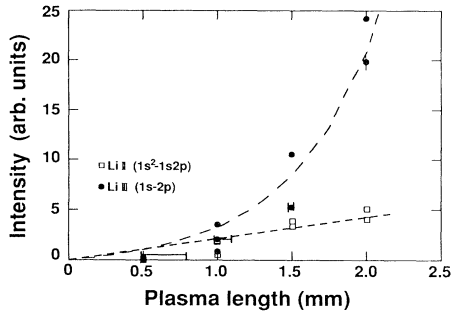

FIG. 5. The 13.5- and 19.9-nm line intensities as a function of plasma length. The dashed curve is a calculated curve of a small-signal gain coefficient of 20 cm^{-1}. Uncertainty in the plasma length determined by the $\cos^2\phi$ distribution of the expanding plasma is shown as error bars.

coefficient of $g=20$ cm^{-1} was obtained for the Lyman-α transition of H-like Li from the fitting.

In order to further confirm the gain of the 13.5-nm transition, we took an off-axis spectrum with a plasma length of 2 mm. When a grazing-incidence spectrograph was tilted by 10 mrad from an optical axis of a subpicosecond KrF laser, the 13.5-nm line intensity decreased to the same level as the 19.9-nm line intensity. By comparing with the on-axis spectra with the same plasma length [Fig. 4(c)], the directionality of the 13.5-nm line emission was ascertained. This anisotropy of the emission strongly supports the gain of the 13.5-nm transition.

The reason why our modified OFI method realized the gain on the Lyman-α transition of the H-like Li ions may be explained by taking account of the difference of the initial conditions of the gain medium. Compared with the original approach using neutral atoms, the use of an ionized medium has two advantages for realizing x-ray lasers pumped by OFI.

The first advantage is to decrease the defocusing effects of a subpicosecond KrF laser pulse. When ions which have high ionization potential exist homogeneously before the subpicosecond KrF laser irradiation, the leading edge of the subpicosecond pulse cannot further ionize the plasma medium since the intensity is not high enough. Therefore, the uniformity of the medium will be maintained until a high-intensity part of the picosecond KrF laser pulse reaches the plasma medium. Singly ionized Li plasma is suitable to satisfy this requirement because the second ionziation potential is high enough. However, when the density of singly ionized Li was higher than 5×10^{17} cm^{-3}, the defocusing effect would become too serious to produce fully stripped ions [20,21]. Therefore, we could not observe the 13.5-nm line at a delay shorter than 300 ns. On the other hand, the 19.9-nm line of the He-like ions did not disappear at a delay shorter than 300 ns. These facts suggest that the defocusing effect decreased the focused intensity of a subpicosecond KrF laser pulse.

The second advantage is that an initial electron temperature before a subpicosecond KrF laser irradiation can be kept sufficiently low. In our experimental conditions, it should be less than 1 eV. If initial electrons are not heated by the subpicosecond KrF pulse, these electrons can play an important role for the rapid three-body recombination of fully stripped ions. In a low electron density condition as in our case, collisional heating within a pump pulse duration of 500 fs will be ignored. Therefore, the initial electrons can maintain a low temperature at the end of the subpicosecond pump pulse.

In conclusion, we have demonstrated the amplification of the 13.5-nm Lyman-α transition of the H-like Li by optical-field-induced ionization. The use of an ionized medium instead of neutral atoms plays important roles for the production of suitable plasma conditions for an optical-field-induced ionization x-ray laser.

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*Permanent address: Department of Electrical Engineering, Keio University, 3-14-1 Kiyoshi, Kohoku-ku, Yokohama 223, Japan.

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