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Highly efficient pulsed power supply system with a two-stage LC generator and a step-up transformer for fast capillary discharge soft x-ray laser at shorter wavelength

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Highly efficient and compact pulsed power supply system for a capillary discharge soft x-ray laser (SXRL) has been developed. The system consists of a 2.2 μF two-stage LC inversion generator, a 2:54 step-up transformer, a 3 nF water capacitor, and a discharge section with a few tens of centimeter length capillary. Adoption of the pulsed transformer in combination with the LC inversion generator enables us to use only one gap switch in the circuit for charging the water capacitor up to about 0.5 MV. Furthermore, step-up ratio of a water capacitor voltage to a LC inversion generator initial charging voltage is about 40 with energy transfer efficiency of about 50%. It also leads to good reproducibility of a capillary discharge which is necessary for lasing a SXRL stably. For the study of the possibility of lasing a SXRL at shorter wavelength in a small laboratory scale, high-density and high-temperature plasma column suitable for the laser can be generated relatively easily with this system. © 2010 American Institute of Physics. [doi:10.1063/1.3276705]

I. INTRODUCTION

A wavelength of a laser has been shortened to a soft x-ray region owing to the progress of pulsed power technology in recent years. It is strongly expected that the soft x-ray laser (SXRL) will be applied to a wide range of fields such as nanotechnology, life science, and elucidation of physical or chemical phenomena. Lasing a saturated SXRL has been demonstrated at a wavelength of as short as 5.9 nm.¹ However, because the lifetime of an excited state of a lasing medium for a shorter wavelength laser becomes much shorter, the required pumping power is inversely proportional to the fourth power of its wavelength and the necessary power will be extremely high.² Moreover, divergence of the radiation in the high-density plasma becomes so significant that the required pumping power should be much higher. Therefore, to realize lasing at shorter wavelength, extremely high pumping power is required which makes it difficult to conduct the basic experiment in a small laboratory.

In 1994, utilizing a fast capillary discharge scheme, lasing of a highly saturated Ne-like Ar SXRL at 46.9 nm has been demonstrated.³ In this scheme, using the Lorenz force of a fast capillary discharge, a hot and dense long plasma column with length of about 10 cm was generated, where an amplification of radiation was obtained by collisional excitation. A pinched plasma column with particle number density of about $5 \times 10^{19} \text{ cm}^{-3}$ and an electron temperature of about 60–90 eV can be efficiently generated by a discharge current of about a few tens of kiloamperes with pulse width of several tens of nanoseconds. Owing to the generation of long

axially uniform discharge plasma column, the capillary discharge SXRL is a promising scheme and its technical basis is being established with the redemonstration of the Ne-like Ar laser in several countries. Taking advantage of a pulsed power system consisting of a Marx generator, a water capacitor and a gap switch, it is possible to generate such a high-density and high-temperature long plasma column by using only several hundreds of joules in a laboratory scale.^{4–9} More recently, in 2005, making use of a very low inductance coaxial configuration without a Marx generator, lasing of 46.9 nm Ne-like Ar laser at a repetition rate of 12 Hz was also demonstrated, resulting in a significant decrease in the size of pumping device to a desktop size.¹⁰

Concerning the generation of a shorter wavelength SXRL pumped by capillary discharge scheme, much effort has been made resulting in an amplification of a 13.2 nm Ni-like Cd line and a 18.2 nm H-like C VI recombination line.^{11,12} However, there is no demonstration of lasing SXRLs of these wavelengths up to saturation because it is still difficult to generate a highly uniform long plasma column with several tens of centimeters in length. Thus, to investigate the possibility of lasing a SXRL at shorter wavelength in a small laboratory scale, highly efficient and compact pulsed power supply system is required. In this paper, development of a highly efficient and compact pulsed power supply system with a LC inversion generator and a step-up transformer for realizing a capillary discharge SXRL at shorter wavelength will be reported.

II. EXPERIMENTAL SETUP

Developed pulsed power system consists mainly of a 2.2 μF two-stage LC inversion generator, a 2:54 step-up

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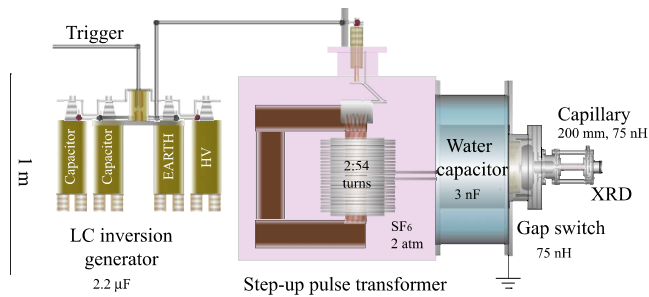


FIG. 1. (Color online) Pulsed power system composed of a two-stage LC inversion generator, a step-up transformer, a water capacitor, a gap switch, and a capillary load.

pulse transformer, a 3 nF coaxial water capacitor, a self-breakdown gap switch, and a capillary load as shown in Figs. 1 and 2. Minimizing stray inductances between the LC inversion generator and the water capacitor, it became possible to transfer a large amount of energy of several hundreds of joules from the 2.2 μF primary capacitor to the 3 nF secondary capacitor rapidly. The inductances of the charging circuit are chiefly composed of a stray inductance of transmission line and a leakage inductance of high voltage step-up transformer. Making use of a LC inversion generator with oil capacitors connected in series and parallel, one external triggered gap switch, 24 coaxial cables (RG-8U) connected in parallel and a wide parallel-plate transmission line, the stray inductance of a charging circuit could be minimized to about 350 nH. In addition, by filling a tank in which the transformer is set with 2 atm SF_6 gas to increase dielectric strength, it became possible to decrease the space which exists between the primary windings and the secondary windings of the step-up transformer. As a result, the leakage inductance of the high voltage step-up transformer could be minimized to around 350 nH. Consequently, total inductance related to the charging system of the water capacitor could be reduced to nearly 700 nH, resulting in rapid charging of a water capacitor within 3 μs . Owing to such rapid charging, it is possible to minimize energy loss, which is caused by resistive discharge through the water to several percents and to avoid the magnetic saturation of the step-up transformer.

With this scheme, initial charging voltage of the primary LC inversion generator could be reduced to several tens of kilovolts, which made the pulsed power system greatly compact. Furthermore, with the help of only one triggered gap switch used for the two-stage LC inversion generator, repro-

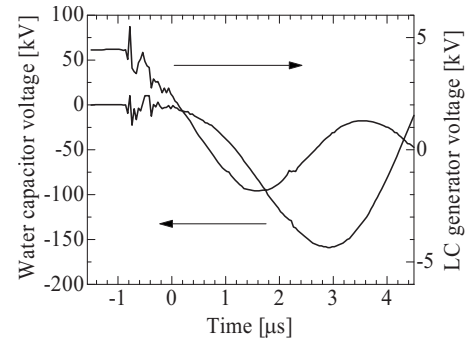


FIG. 3. Voltage waveforms of the water capacitor and the LC inversion generator.

ducibility of discharge was greatly improved and energy loss caused by the gap switch was dramatically reduced compared to the case of using a conventional Marx generator.

The discharge section consists of a gap switch and a capillary load with length of 20 cm. Pressurization of the self-breakdown gap switch with SF_6 gas of 1–3 atm enables gap length to be shortened as short as a few centimeters, which leads to realizing a compact and simple geometry with relatively low stray inductance. In addition, by utilizing a coaxial line with larger inner and smaller outer radii, the stray inductance has been minimized. With the use of a long acrylic insulating plate effectively to avoid the surface discharge, total stray inductance of a load capillary section is about 150 nH with a 20 cm long capillary. Consequently, with this compact and simple discharge section, stable and easy operation can be possible with relatively low inductance. Utilizing this pulsed power system, radiation from the Ar gas was measured to confirm lasing of a Ne-like Ar SXRL at 46.9 nm. In the experiment, an x-ray diode with a gold cathode was used to measure the radiation emitted from the capillary plasma.

III. RESULTS AND DISCUSSION

A step-up ratio of the water capacitor voltage to the initial charging voltage of the LC inversion generator was measured by using a capacitive divider. The voltage waveforms shown in Fig. 3 are those of the water capacitor and the LC inversion generator. Initially, the capacitor of LC inversion generator is charged to 4.5 kV. When the gap switch of the generator is closed, charging of the water capacitor starts at zero time. Obtained water capacitor voltage reaches 160 kV

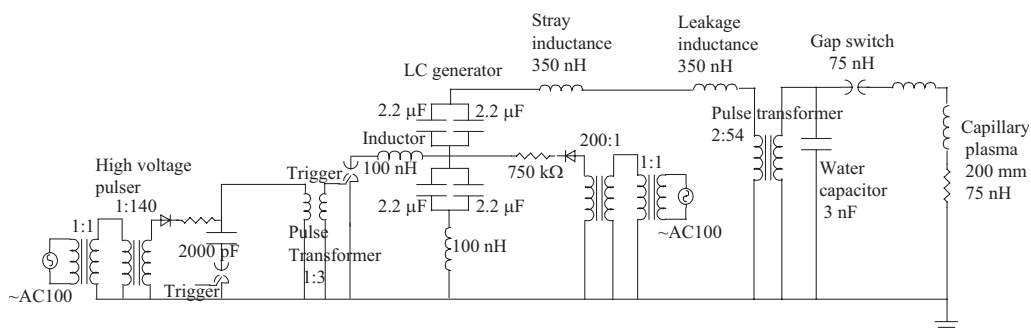


FIG. 2. Circuit diagram of pulsed power system.

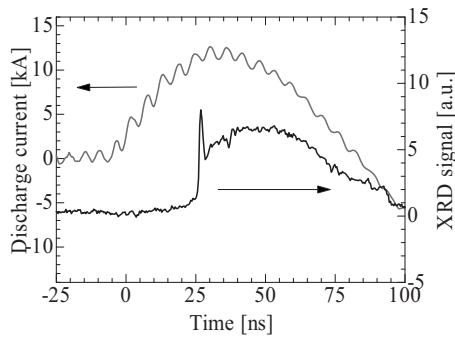


FIG. 4. Lasing of a 46.9 nm Ne-like Ar SXR laser. Initial capacitor voltage of the LC inversion generator was 3 kV.

and energy stored in the LC inversion generator is transferred to the water capacitor within 3 μs . This rapid charging of the water capacitor minimizes the energy loss of the water capacitor and avoids the saturation of the core used for the pulse transformer. Taking advantage of the two-stage LC inversion generator with one triggered gap switch and the low leakage inductance transformer, about 50% of the energy initially stored in the LC inversion generator is transferred to the water capacitor. Owing to this highly efficient, two-stage LC generator with a step-up transformer system, the measured step-up ratio with respect to the initial charging voltage of LC inversion generator reaches approximately as high as 40.

Using the system, lasing of a Ne-like Ar SXRL at a wavelength of 46.9 nm has been demonstrated. In experiment, an alumina ceramics capillary with an inner diameter of 4 mm was filled with 20 Pa Ar gas. The Ar plasma was preionized by utilizing a RC discharge with current amplitude of 10 A and a time constant of 10 μs to generate an axially uniform pinched plasma by suppressing the growth of instabilities.⁴ Initially, a capacitor of the LC inversion generator was charged to 3 kV. A few microseconds after the start of the predischage, the main discharge current was initiated with peak current amplitude of about 13 kA and rise time of about 25 ns, resulting in generation of the SXRL spikes in x-ray photo diode (XRD) signals, as shown in Fig. 4. In Fig. 4, the start time of a current flow after the initiation of the main discharge is set to 0. That the spike of the Ne-like Ar SXRL can be observed shows the validity of this pulsed power system.

Concerning the development of high power pumping system for lasing a SXRL at the shorter wavelength, high voltage experiment was conducted with this power supply system. Initially, the capacitor of the LC inversion generator was charged to 12.5 kV and an externally triggered spark gap switch was closed to initiate the charging of the water capacitor. As a result, the water capacitor was charged to about 0.5 MV, as shown in Fig. 5. In Fig. 5, zero time corresponds to gap breakdown. The discharge current started to flow when water capacitor reached its maximum voltage. Using this highly efficient and compact pulsed power supply system, it is possible to generate a discharge current with amplitude of about several tens of kiloamperes through a moderately long capillary, which is required for the generation of

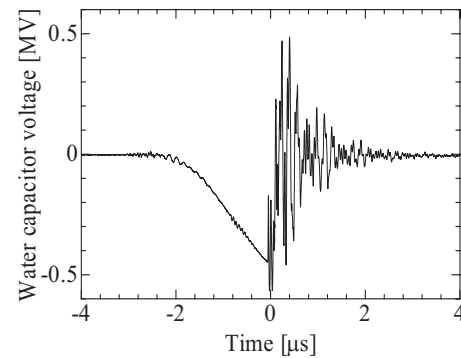


FIG. 5. Water capacitor voltage with self-breakdown gap switch closed.

high-density and high-temperature plasma column adequate to study the possibility of SXRL at shorter wavelengths. This demonstrated that taking advantage of using this system, realization of high power SXRL becomes possible in a small laboratory scale.

IV. SUMMARY

A highly efficient and extremely compact pulsed power supply system for generation of a capillary discharge SXRL has been developed. The power supply system consists of a two-stage 2.2 μF LC inversion generator, a 2:54 step-up transformer, a 3 nF water capacitor, and a 20 cm capillary load with about 150 nH. The step-up ratio of the water capacitor voltage to the LC inversion generator voltage was measured to be about 40 with an energy transfer efficiency of about 50%. As a result, utilizing this pulsed power system, lasing of a Ne-like Ar SXRL has been demonstrated with charging voltage of only 3 kV in a primary capacitor. Further, when the LC inversion generator was charged up to 12.5 kV, water capacitor voltage reached about 0.5 MV, which leads to a generation of higher-temperature and higher-density plasma column with length of a few tens of centimeters adequate to study the possibility of a SXRL at shorter wavelength.

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