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Performance of soft x-ray laser pumped by capillary discharge

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Abstract

We report the output characteristics of capillary discharge single-pass 46.9 nm Ne-like Ar soft-X-ray laser generated by a capillary z-pinch discharge. The coherence properties of the laser have shown to be improved with the increase of the length of laser amplifier from 20 up to 35 cm. The high degree of the spatial coherence of the laser beam produced by 35 cm long capillary is demonstrated by the results obtained in a classical Young's double-slit experiments. We found that the coherence length of the laser is 50 μm. For the 20 cm-long capillary, the diameter of a laser beam is in a range from 3.2 to 4.0 mm, which is corresponding to a range of divergence from 2.2 to 2.8 mrad. Finally, we introduce two spikes on X-ray diode (XRD) signal observed in a single shot.

KEYWORDS: capillary discharge, Z-pinch, soft X-ray laser, spatial coherence, coherence length, beam spot size, beam divergence.

1. Introduction

A laser has some excellent properties such as monochromaticity, high intensity, and coherency. These characteristics have made the laser more attractive than an ordinary light. For a soft X-ray laser, especially, its short wavelength enables material manipulations at molecular level. This has attracted great research interests in producing soft X-ray sources, because the above-mentioned properties have been urgently expected by some pioneering scientific application, such as biotechnology, X-ray holography, X-ray microscopy, and the diagnostics of dense plasma [1,2,3,4]. However, the excitation power for such soft X-ray lasing follows a 4.5 power rule of the lasing frequency. Producing an intense laser of shorter wavelength will therefore require a device of extremely large scale such as synchrotrons, which usually leads to high cost.

A novel table-top soft X-ray source, which is using Z-pinch plasma produced by capillary discharge, has been proposed. It is capable of generating high output laser, repeatable in operation and, most importantly, compact in size and low in cost. The process in generation of Ne-like Ar soft X-ray laser is as follows. Once discharge current pulse of ~30 kA is applied to the capillary filled with preionized argon gas, a plasma column is formed with an electron temperature of 60-80 eV and an electron density of $0.2\text{-}2\times10^{19}$ cm^{-3} due to the Z-pinch compression, which results in the generation of the population inversion for the 3p-3s transition that is required for the Ne-like Ar lasing. In 1995, Rocca *et al* demonstrated the lasing of Ne-like Ar soft-X-ray laser (3p-3s transition, wavelength is 46.9 nm) by the above-mentioned method, using a capillary with inner diameter of 3-4 mm and argon gas pressure of 6-100 Pa [5]. A spike in XRD output signal similar to Rocca's has been observed and reported in our previous works [6,7], which has been proven as Ne-like Ar lasing (J=0-1, μ=46.9 nm) by spectroscopy [8]. In this paper, we have evaluated the characteristics of the Ne-like Ar soft-X-ray laser, such as spatial coherence and divergence. We found that the coherence of the laser were improved by increasing the length of capillary discharge plasma from 20 up to 35 cm. High degree of spatial coherence of the laser beam produced by 35 cm long capillary has been demonstrated. A convenient measuring method for the divergence of the laser beam has been proposed. And we found two spikes on XRD signal in a single shot using a 35 cm-long capillary.

2. Experiment setup

The device used in this experiment is schematically shown in Fig. 1. We used a capillary with an inner diameter of 3 mm and a length of 200 mm or 350 mm, which is made of Al_2O_3 ceramics to reduce the degree of ablation from the inner wall.

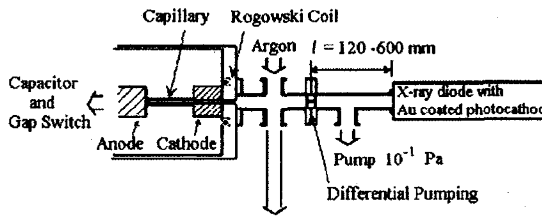


Fig. 1. Schematic diagram of the experimental apparatus

The discharge system is driven by a pulsed power supply as shown in Fig. 2, which consists of a 3-stage Marx generator, a 2:28 step-up transformer and a pulse-forming line (PFL) made of a water capacitor. The impedance of the PFL is 5.5Ω. The gas in a capillary is predischarged by a current of ~20 A, which is provided by a separate circuit. The maximum output voltage of the Marx generator is 60 kV, which subsequently yields a

PFL output voltage of 430 kV. With this power supply system, it is able to obtain a discharge current pulse up to 32 kA. In this experiment, the system is operated at 1 pulse per minute. The time evolution of laser output power is detected by an X-ray diode (XRD). The XRD used is schematically shown in Fig. 3. The photocathode is made of gold, which enables a sensitive detection of X-ray from 10 to 100 eV [9]. In order to reduce the noise from the background radiation and the reabsorption of laser light by the neutral argon gas between the end of capillary and the XRD, a pinhole of 1 mm in diameter is located at a distance of 15 mm from the end of the capillary and the section between them is differentially pumped. The distance between the pinhole and the XRD is adjustable in order to obtain a qualitive indication of the directivity of the laser. A negative bias voltage of 800 V is applied to the photocathode of the XRD with respect to its mesh anode, and they are separated by a distance of 2 mm. When a laser spot has an diameter of 2 mm, the output of XRD is estimated to saturate at a current of 0.45 A, which corresponds to an output voltage of 22.5 V.

3. *Experimental results*

3.1 Beam divergence

As shown in Fig. 3, an aperture of 4 mm in diameter has been adapted in front of the mesh anode to eliminate the background radiation. The XRD is located at a distance of 72 cm from the end of the capillary. A bellows is adapted at the upstream end of the drift tube, which enables adjustment of the location of the XRD without breaking vacuum. Two series of the experiments have been conducted to measure the beam size of the SXR laser by changing the location of the XRD horizontally (x direction) and vertically (y direction), where the center of the beam is set initially in the vicinity of the origin of coordinates. Fig.4 (a) shows the XRD output measured by changing the location of the XRD horizontally. The laser signal is observed in a range from –4.0 to 4.0 mm, which corresponds to a range of 8.0 mm and is relatively symmetrical with respect to the center of the beam axis. This indicates that the beam spot has a diameter of 4.0 mm, since the aperture radius of 2 mm has to be subtracted from both sides. Fig.4 (b) shows the plots of the results measured by changing the position of the XRD vertically. It is seen that the axial symmetry in vertical direction becomes worse than that in horizontal direction. The laser signal is observed in a range of 7.2 mm from –3.2 to 4.0 mm, which corresponds to a beam size of 3.2 mm. This result indicates that the cross section of the beam is not circular and its diameter varies from 4.0 to 3.2 mm. The range of the beam diameter obtained above corresponds to a range of beam divergence from 2.2 to 2.8 mrad. However, we cannot obtain the beam diameter from the full width at half maximum of the beam intensity because it is not possible to obtain the radial distribution of laser intensity. Efforts will be made in the future to reduce the diameter of the aperture or use a slit for deducing the laser beam diameter.

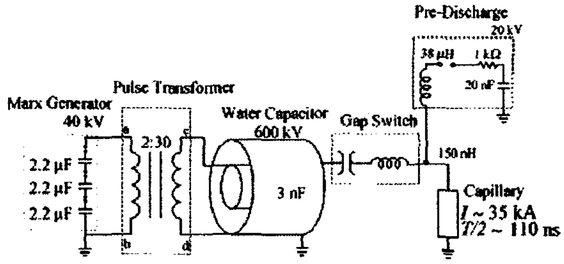


Fig. 2. The power supply system

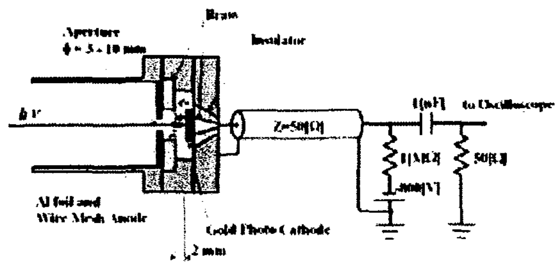


Fig. 3. Schematic diagram of the X-ray diode

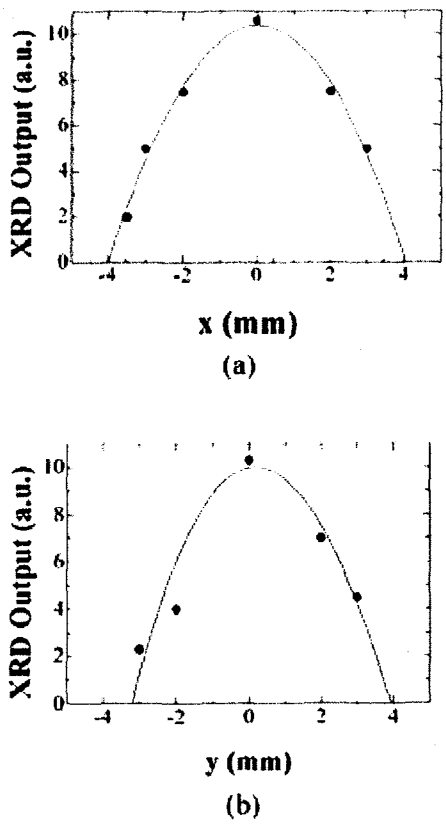


Fig.4. XRD output measured by changing the position of XRD horizontally (a) and vertically (b).

3.2 Spatial coherence

Schematic diagram of classical Young's double slit experiment using a tungsten wire is shown in Fig.5. In this experiment, we have used a cylindrical thin tungsten wire with a diameter of 50 μm or 100 μm. Double-slit interference fringe pattern of the laser was detected by an X-ray CCD camera having 1024×1024 pixels and 13 μm pixel size. We used also an Al filter with a thickness of 0.8 μm to reduce the intensity of laser and cut off the background radiation. Distance between the double-slit and the X-ray CCD is 580 mm or 1070 mm as shown in Fig.5. From Fig.6 (a) and (b) it is shown that the coherence of the laser is improved with increasing the length of lasing medium from 20 cm up to 35 cm. This indicates that the aspect ratio of the plasma column has been increased and only the central part of the laser, which has a good spatial coherence without being refracted by electron density antiguiding, can reach the wire double-slit[10,11].

Comparing interference fringe pattern of Fig.6 and 7, we can see that the contrast of interference fringes becomes more distinct with increasing distance between the double-slit and the screen, from 580 mm to 1070 mm because the intervals of interference fringes are larger. From the interference fringes shown in Fig.7 (a) and (b), which are obtained by using a wire with a diameter of 50 μm and 100 μm, respectively, we have confirmed that the wavelength of the laser is 46 ± 0.9 nm and 46 ± 1.2 nm. The result is in good agreement with the wavelength of Ne-like Ar soft-X-ray laser (3p-3s transition, 46.9 nm). And the coherence length[12] of the laser is obtained to be 50 μm.

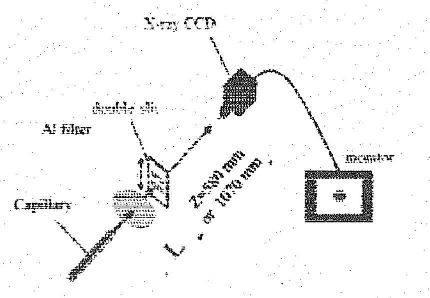


Fig.5 Schematic diagram of Young`s double slit experiment using tungsten wire.

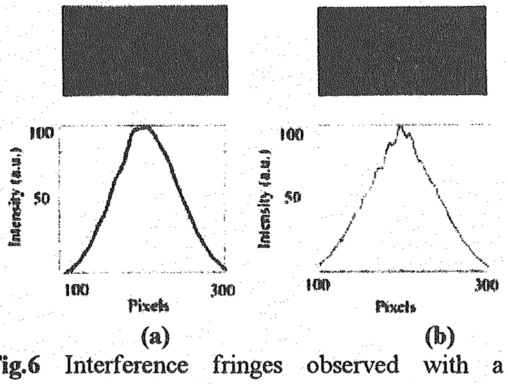


Fig.6 Interference fringes observed with a wire double-slit (wire diameter = 50 μm) using (a): 20cm or (b): 35 cm-long capillary. Distance between double-slit and X-ray CCD camera is 580 mm.

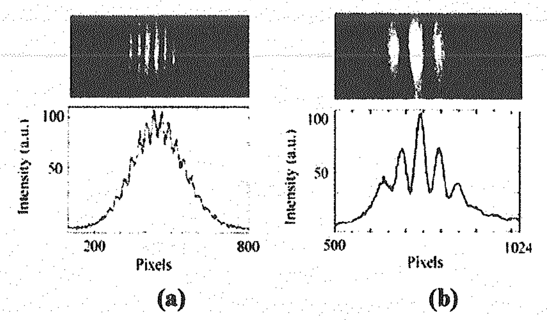
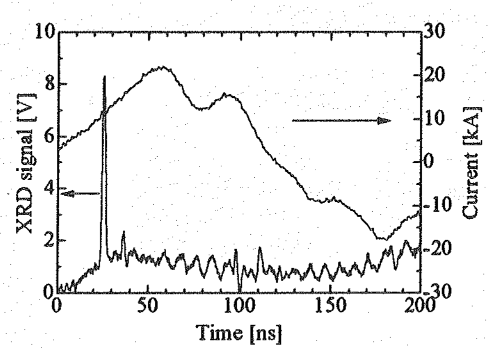


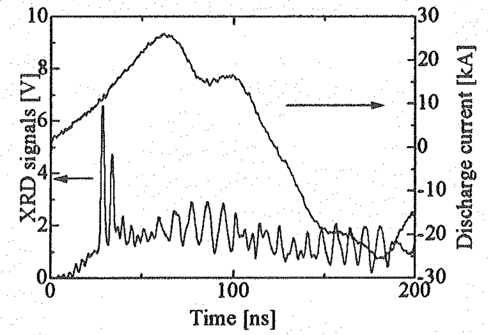
Fig.7. Interference fringes obtained by a wire double-slit ((a): wire diameter = 50 μm, (b): wire diameter = 100 μm) using a 35 cm-long capillary. Distance between double-slit and X-ray CCD camera is 1070 mm.

3.3 Two spike of XRD

Using a capillary with a length of 35 cm, we sometimes observe two spikes of XRD signals as shown in Fig.8. The second spike is observed about 5 ns later than the first one. According to the report by the group of Czech researchers, there is a possibility to obtain a Be-like Ar 2p-2s transition (λ is 42.6 nm) by recombination excitation. To evaluate the second spike, spectroscopic measurement is needed.



(a) One spike



(b) Two spikes

Fig.8 XRD signal from discharge in a 350 mm-long ceramics capillary. (a) : One spike in XRD signal. (b) : Two spikes of XRD signal.

4. Conclusion

We report the output characteristics of capillary discharge single-pass 46.9 nm Ne-like Ar soft-X-ray laser. For the 20 cm-long capillary, divergence of laser beam is measured to be 2.2 to 2.8 mrad. By Young's double slit experiment using a cylindrical tungsten wire, we confirmed that the wavelength of soft-X-ray laser is 46.9 nm. Coherence of the laser has been improved with increasing the length of laser medium from 20 cm up to 35 cm and the coherence length of the laser is found to be 50 μm. Finally we observed two spikes of X-ray diode (XRD) signal in a single shot, which indicates the possibility of lasing by recombination excitation.

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