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Demonstration of multi-pass amplification of 46.9 nm laser pumped by capillary discharge

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ABSTRACT

Using a plane–plane resonator composed of silicon carbide mirrors, we achieve for the first time multi-pass amplification of a 46.9 nm laser pumped by capillary discharge. In terms of the temporal characteristics, for an initial argon pressure of 17 Pa, triple-pass amplification of the laser is obtained at a delay time between the pre-pulse and the main pulse currents of 40 μs, and quadruple-pass amplification is obtained at a delay time of 50 μs. The experimental results show that the gain duration of the plasma column is more than 6 ns. In terms of spatial characteristics, the spot of the output laser has a reduced full width at half maximum divergence compared with that from a laser without a resonator.

I. INTRODUCTION

X-rays play an important role in investigating matter under extreme conditions of temperature, density, pressure, field strength, etc.[1,2] Adding a resonator to a soft x-ray laser can enhance beam quality, spatial coherence, and other characteristics. However, owing to low reflectivity, easy damage of the cavity mirror by plasma bombardment, short gain duration, and other factors, it is difficult to use such a resonator in soft x-ray and extreme ultraviolet (EUV) lasers whose gain medium is a plasma. Currently, laser amplification is mainly obtained in a single pass without feedback. To the best of our knowledge, there has been only one report of an experimental investigation of triple-pass amplification of a soft x-ray laser with a resonator, namely, the 1988 study by Ceglio *et al.*,[3] who used Mo/Si multilayer reflectors. However, these multilayer mirrors were broken by plasma bombardment after one laser pulse. Other studies by Ceglio *et al.*[4] and by other research groups[5–7] also found that multilayer mirrors were easily damaged when used to obtain half-cavity amplification of soft x-ray lasers. In 1996, Rocca *et al.*[8] achieved half-cavity amplification of a 46.9 nm laser by using a rear mirror made of iridium (Ir). However, it was difficult to conduct regular experiments, since the Ir mirror was destroyed after one to three discharge shots. No further studies of multi-pass amplification of soft x-rays have been reported since the 1988, although there have been many publications concerning double-pass amplification of soft x-rays. The difficulty in choosing a suitable output mirror is one of the reasons for this lack of studies. Both the fragility of the output mirror and the strong absorption of soft x-rays by the output mirror are problems that need to be solved.

In 2016, our group achieved double-pass amplification of a 69.8 nm laser by a high-precision polished silicon carbide (SiC) plane mirror.[10] Because of the high hardness of the SiC mirror, its reflectance could remain constant after hundreds of discharges. This enables some regular experiments with half-cavity-amplified lasers to be carried out using SiC mirrors. In 2021, we achieved half-cavity amplification of a 46.9 nm laser using a SiC plane rear mirror.[11] The half-cavity-amplified 46.9 nm laser had a pulse amplitude 2.4 times greater than that of a single-pass-amplified laser and a full width at half maximum (FWHM) that was wider by 0.9 ns. With the half-cavity-amplified laser pulse, the gain duration of the plasma column could exceed 4 ns. These results demonstrate that it is feasible to realize multi-pass amplification of a 46.9 nm laser using a resonator composed of SiC mirrors.

In the work described in this paper, based on the experiments with a half-cavity-amplified laser reported in Ref. 10, a SiC plane mirror with a central hole was placed at the output end face of a capillary to realize amplification of a 46.9 nm laser using a resonator. An output laser with reduced divergence and more concentrated energy distribution was obtained. In addition, the reflectance of the SiC mirrors remained constant for 200 discharge shots. This setup provides a practical 46.9 nm laser with high coherence, with which it should be possible to conduct regular experiments.

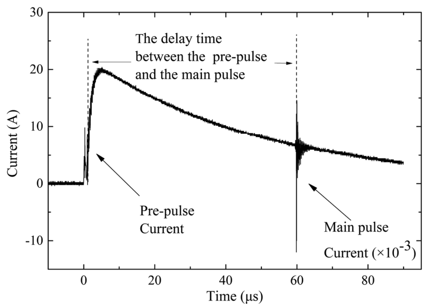

FIG. 1. Process of capillary discharge. The main pulse current was reduced by a factor of about 1000.

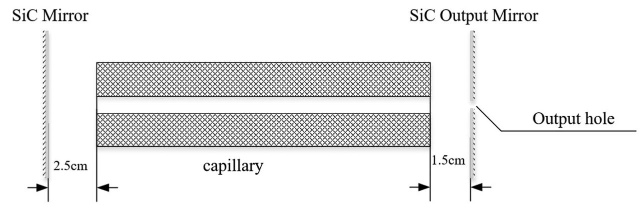

FIG. 3. Plane–plane resonator of 46.9 nm laser.

II. EXPERIMENTAL SETUP

The length of the Al_2O_3 capillary used in the experiment was 35 cm, and its inner diameter was 3.2 mm. The process of capillary discharge is shown in Fig. 1. First, the capillary was filled with argon (Ar) at a pressure of 17 Pa. This gas was then ionized into an initial plasma by a pre-pulse current of 20 A. The delay time between the pre-pulse and the main pulse Δt was 40–60 μs. After the delay time, a main current of 13 kA with an FWHM pulse width of about 70 ns was passed through the initial plasma, as shown in Fig. 2. The magnetic pressure generated by the main pulse was greater than the thermodynamic pressure, as a consequence of which the initial plasma was compressed. During the final stage of the compression, the plasma column reached the condition to provide gain for the 46.9 nm laser by collisional excitation.[9] According to the results of the double-pass amplification experiments,[10] the gain can last for more than 4 ns.

A schematic of the plane–plane resonator used in the experiment is shown in Fig. 3. The reflectance of the SiC plane mirror for soft x-rays at 46.9 nm was about 4%, as measured by the MLS synchrotron radiation facility at the Physikalisch-Technische Bundesanstalt (PTB). An SiC plane mirror with a 300 μm diameter central circular hole was placed 1.5 cm from the output end face of the capillary. Any part of the laser beam falling outside the hole was reflected into the capillary. Another SiC plane mirror was placed 2.5 cm from the opposite end of the capillary. Using this resonator, multi-pass amplification of the 46.9 nm laser could be realized. An x-ray diode (XRD) with a wire-mesh anode and a gold-layer cathode was used to measure the temporal characteristics of the laser. A charge-coupled device (CCD; Andor iKon-M) was placed 2.4 m from the output end face of the capillary to measure the spatial characteristics of the laser.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The output characteristics of the 46.9 nm laser amplified by a resonator were examined using the XRD and CCD. First, the temporal characteristics of the laser at Δt = 60 μs were measured by the XRD. The laser pulse is shown in Fig. 4. As can be seen, there are three distinct peaks (corresponding to the first-, second-, and third-pass amplifications). The time difference between the first and second peaks is about 0.9 ns. The optical path difference between the first- and second-pass amplifications is 40 cm, and so the theoretical time difference between the first and second peaks is 1.3 ns. The overlap between the first pulse and the rising edge of the second pulse results in a reduction of this time difference. The time difference between the second and third peaks is about 1.3 ns. Since the optical path difference between the second- and third-pass amplifications is 38 cm, the theoretical time difference between the second and third peaks is about 1.27 ns, which is almost the same as the experimental result.

As can be seen in Fig. 4, the intensity of the second-pass-amplified laser is higher than that of the first-pass-amplified laser, which is a consequence of the longer gain duration. Figure 4 also demonstrates that the plasma column still provides a gain for the laser during the third-pass amplification. However, the intensity of the third-pass-amplified laser is lower than that of the first-pass-amplified laser. To understand why this intensity is lower, the propagation process of the laser in the plasma column needs to be

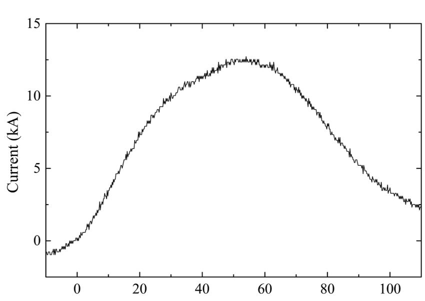

FIG. 2. Main pulse used in the experiment.

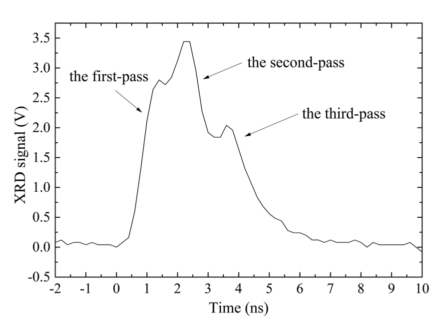

FIG. 4. Pulse obtained from the 46.9 nm laser with a resonator.

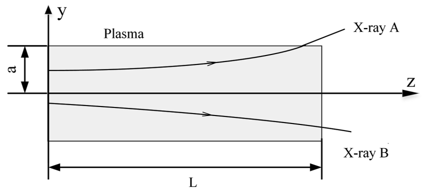

FIG. 5. Schematic of the plasma column: x-ray A is representative of the x-rays emerging from the side near the end face of the plasma column, and x-ray B is representative of the x-rays emerging from the end face.

considered. The propagation path of the x-rays in the plasma column is shown in Fig. 5, in which x-ray A is representative of the x-rays emerging from the side near the end face of the plasma column, and x-ray B is representative of the x-rays emerging from the end face. For a long plasma column, the laser output is primarily composed of x-rays of these two types, which together determine the output characteristics.[12] The propagation distance of the third-pass-amplified laser is longer than that of the first-pass-amplified laser. Compared with the first-pass-amplified laser, more of the third-pass-amplified laser will emerge from the side of the plasma column, like x-ray A here, owing to the effect of refraction. Therefore, only a part of the third-pass-amplified laser can emerge from the output hole, which results in a reduction in intensity compared with the first-pass-amplified laser.

As the plasma state deviates from the ideal condition, the amplitude of the second pulse peak is small, which is why the three peaks in Fig. 4 can be distinguished clearly. When the plasma state is relatively close to ideal, the pulse amplitude of the second-pass-amplified laser will be larger, resulting in overlap of the three peaks of the laser pulse. The multi-pass-amplified laser pulse at Δt = 40 μs for a resonator with an initial pressure of 17 Pa is shown in Fig. 6, together with the pulse obtained in the absence of a resonator. The time difference between the second and third peaks of the pulse from the laser with resonator is again about 1.3 ns. The amplitude of the second peak, corresponding to the second-pass amplification, is 1.4 times greater than that of the first peak, whereas the amplitude of the third peak, corresponding to the third-pass amplification, is almost equal to that of the first peak. Compared with the pulse from the laser without a resonator, the FWHM of the triple-pass-amplified pulse is widened by about 1.7 ns. Figure 6 also demonstrates that

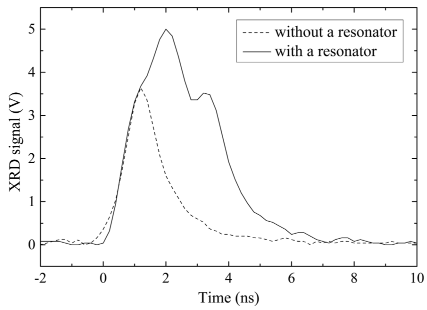

FIG. 6. Laser pulses at Δt = 40 μs with and without a resonator with an initial pressure of 17 Pa.

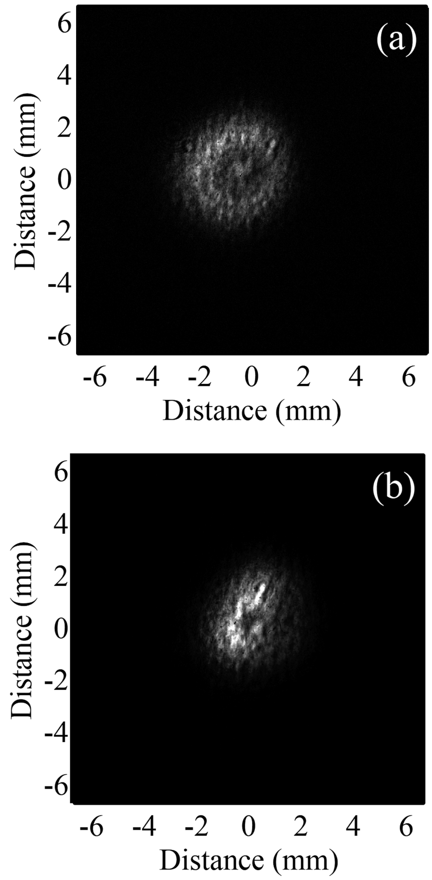

FIG. 7. Laser spots at Δt = 40 μs: (a) without and (b) with a resonator with an initial pressure of 17 Pa.

the gain duration of the plasma column reaches more than 6 ns. Similar to the multi-pass-amplified laser pulse shown in Fig. 4, the third-pass-amplified pulse shown in Fig. 6 is also affected by the effect of refraction, as a consequence of which the intensity of the third-pass-amplified laser is equal to that of the first-pass-amplified laser.

The spatial characteristics of the output laser with and without a resonator were measured by the CCD and are shown in Fig. 7. The results in Fig. 7(a) were obtained using a steel slice with an output hole of 300 μm. The spot from the laser without a resonator has an annular structure with a center peak. By contrast, the spot from the multi-pass-amplified laser is more concentrated. To compare the spatial distributions in the cases with and without a resonator, the radial distribution curves in the horizontal direction are shown in Fig. 8 (where high-frequency noise has been removed to allow a clear comparison). The FWHM divergence of the laser spot in the absence of a resonator is about 1.37 mrad, whereas that when the resonator is used is smaller: about 0.37 mrad.

In Fig. 9, multi-pass amplification can be observed at both Δt = 50 and 60 μs. At Δt = 60 μs, there is clear triple-pass amplification. At Δt = 50 μs, the time difference between the last pulse peak at 4.4 ns and the first pulse peak is about 3.7 ns, which is longer than

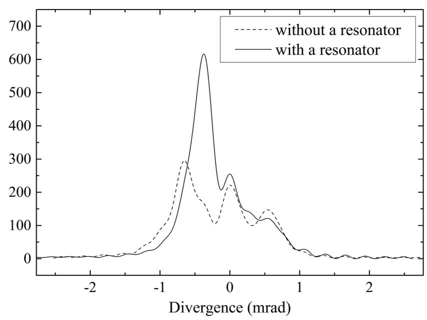

FIG. 8. Radial distribution curves of output laser spots with and without a resonator.

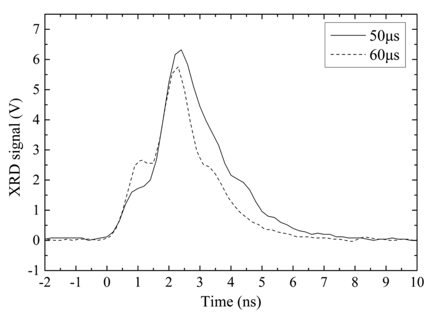

FIG. 9. Output laser pulses at Δt = 50 and 60 μs with a resonator.

2.6 ns (the theoretical time difference between the first and third pulse peaks). Because the optical path difference between the fourth- and first-pass amplifications is about 116 cm, the corresponding theoretical time difference is about 3.87 ns, which is nearly equal to the measured time difference of 3.7 ns. Taking account of the measurement error caused by the overlap of the third and fourth pulse peaks, we can consider that a quadruple-pass-amplified laser is obtained at Δt = 50 μs. In addition, the amplitudes of the fourth and first pulse peaks are almost equal. These experimental results prove that the plasma column still provides a gain for the 46.9 nm laser when the fourth-pass-amplified laser propagates in the column.

Analysis of the experimental results in terms of geometric optics shows that the small electron density gradient in the plasma column may be the main reason why the quadruple-pass-amplified laser can be observed at Δt = 50 μs. As shown in Fig. 5, x-ray A will be concentrated near the refraction angle ϕ_r, which is related to the maximum electron density n_e and the critical electron density n_c through the expression $\phi_r = (n_e/n_c)^{1/2}$.[13] Correspondingly, x-ray B will be concentrated near the axis of the plasma column. As shown in Figs. 3 and 5, only the laser represented by x-ray B can re-enter the plasma column after reflection by the SiC mirrors. The laser spots at Δt = 40 and 50 μs in the absence of the resonator are shown in Fig. 10. As can be seen, the spot at Δt = 40 μs is annular, with a small divergence angle and high intensity. However, the spot at Δt = 50 μs is flat at the same position, which means that more x-rays of the type represented by x-ray B in Fig. 5 emerge from the plasma column at Δt = 50 μs. Therefore, the spatial distribution at Δt = 50 μs is more suitable for multi-pass amplification of the 46.9 nm laser. The spatial distribution of the output laser without a resonator is influenced by the electron density distribution of the plasma column.[12–15]

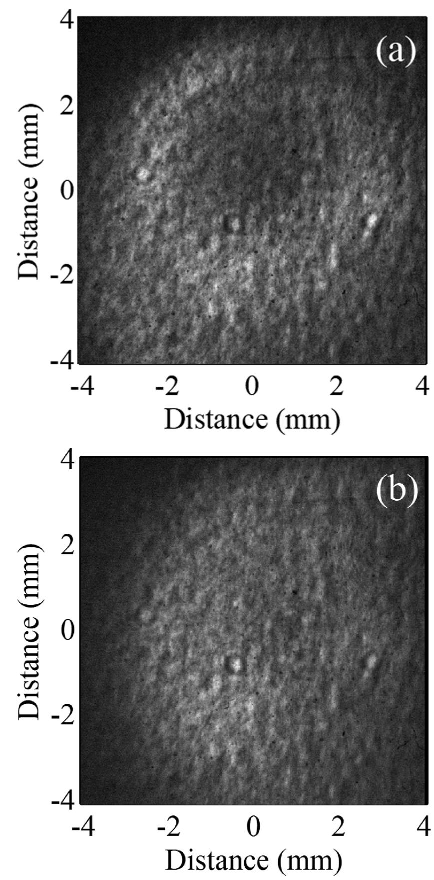

FIG. 10. Laser spots at Δt = 40 μs (a) and 50 μs (b) without a resonator.

We assume that the radial inhomogeneity of the initial plasma causes the electron density distribution to vary with Δt as described in Ref. 16, which ultimately leads to variation of the laser spot with Δt. According to Ref. 16, the radial spatial distribution of the initial plasma is inhomogeneous and changes with time. Different values of Δt will lead to differences in the initial plasma column state when the main pulse current flows through the column. These different states will affect the Z-pinch process and the plasma state when the 46.9 nm laser is generated. The small electron density gradient enables more x-rays to be concentrated near the axis of the plasma column. In addition, when the electron density distribution is smaller, the x-ray propagation in the plasma column will be less affected by refraction, which will lead to a larger gain–length product. Therefore, the smaller the electron density gradient in the plasma column, the more suitable it is for multi-pass amplification. At Δt = 50 μs, there are more x-rays concentrated near the axis of the plasma column than at Δt = 40 μs, and so the plasma column has a smaller electron density gradient at Δt = 50 μs. Therefore, with a resonator at Δt = 50 μs, it is possible to obtain more intense feedback and a greater gain–length product. This may be why quadruple-pass amplification of the 46.9 nm laser can be observed at Δt = 50 μs, whereas only triple-pass amplification can be achieved at Δt = 40 μs.

The above analysis demonstrates that the electron density distribution in the plasma column has an effect on the amplifications of the laser in the resonator. As shown in Fig. 5, a soft x-ray propagating in the plasma column has a curved trajectory owing to the effect of refraction, which is different from the propagation process of a long-wavelength laser in a gain medium. Therefore, the experimental results on multi-pass amplification of a 46.9 nm laser presented in this paper are helpful in providing a deeper understanding of resonator theory for soft x-ray lasers.

IV. SUMMARY

A plane–plane resonator was applied to a 46.9 nm laser. The output mirror was a SiC plane mirror with a 300 μm diameter circular hole. Third-pass amplification of the laser was obtained at an initial pressure of 17 Pa and a pre–main delay time of 40 μs. The amplitude of the output laser pulse with the resonator was found to be 1.4 times greater than the amplitude in the absence of the resonator, and the FWHM of the output laser pulse was widened by about 0.9 ns when the resonator was used. The amplitude of the third pulse peak was almost equal to that of the output laser without a resonator. The experimental results also showed that the gain duration of the plasma column was more than 6 ns. When Δt = 50 μs, quadruple-pass amplification was achieved, with the amplitude of the fourth pulse peak being almost equal to that of the first. The multi-pass amplification experiments performed here have provided deeper understanding of the effect of the electron density distribution and the gain duration of the plasma column on the 46.9 nm laser. In the future, a concave mirror will be used as the rear mirror to reduce the influence of refraction on the laser divergence. In this case, an output hole of the appropriate diameter will need to be chosen taking account of the radius of curvature of the concave mirror.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Dongdi Zhao: Conceptualization (lead); Data curation (equal); Formal analysis (equal); Investigation (lead); Writing – original draft (lead); Writing – review & editing (equal). **Yongpeng Zhao**: Conceptualization (lead); Data curation (equal); Formal analysis (equal); Investigation (lead); Writing – original draft (lead); Writing – review & editing (equal). **Bo An**: Investigation (equal); Writing – review & editing (equal). **Jiaqi Li**: Investigation (equal); Writing – review & editing (equal). **Huaiyu Cui**: Investigation (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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