Experimental investigation of double-pass amplification of an x-ray laser in neonlike germanium

He Shaotang, Chunyu Shutai, Zhang Qiren, He An, and Shen Huazhong
Southwest Institute of Nuclear Physics and Chemistry, P.O. Box 525-77, Chengdu 610003, China

Ni Yuanglong and Yu Songyu
High Power Laser and Physics Laboratory, P.O. Box 8229, Shanghai 201800, China
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Experimental investigations of double-pass amplification of an x-ray laser in Ne-like germanium were carried out at the Shengguang laser facility (of the High Power Laser and Physics Laboratory, Shanghai, China). In these experiments a molybdenum-silicon multilayer mirror was used at normal incidence, and a flat-field grating spectrograph was used to measure the intensities of the laser lines. We observed double-pass emission intensity in Ne-like Ge at 23.2 and 23.6 nm that was five times larger than that of the single-pass amplified spontaneous emission. The damage of the multilayer mirror irradiated by laser plasma was measured simultaneously, the lifetime of Mo-Si multilayer mirror was about 440–700 ps. In addition, we measured the beam divergence of the lasing beam; the results showed that the beam divergence in the vertical direction was about 22 mrad and in the horizontal direction about 12 mrad. Also, the beam optics of the double-pass signal was observed.

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I. INTRODUCTION

Recently there have been significant advances in the generation of amplified spontaneous emission (ASE) at extreme ultraviolet (XUV) and soft-x-ray wavelengths [1–9], in addition to dramatic progress in the development of efficient, normal incidence mirrors for soft x rays [10]. These developments offer the ultimate promise of resonant multipass x-ray laser cavities with improved efficiency and optimized divergence and coherence properties. Experimental investigations of double-pass amplification of x-ray lasers have been reported by Ceglio [11]. An x-ray laser cavity composed of the molybdenum-silicon multilayer mirrors was used and $2-3\times$ enhancement of the double-pass amplification signal in Ne-like selenium at 20.63 and 20.96 nm was observed. Since then, several reports have been published in the technical literature [12,13].

We have recently carried out the double-pass amplification experiments of an x-ray laser at 23.2 and 23.6 nm in Ne-like Ge. With Mo-Si multilayer mirrors, we demonstrated the explicit double-pass amplifications, observed the damage of a multilayer mirror irradiated by laser plasma, and measured the lifetime of the mirror and the x-ray laser beam divergences in the horizontal direction and the vertical direction; also, we observed the beam optics of the double-pass signal.

II. EXPERIMENTAL METHODS

These experiments were carried out at the Shengguang laser facility with a pumping laser wavelength of 1.05 μm, a pulse duration [full width at half maximum (FWHM)] of about 1 ns, and an energy of 550 J delivered to the target in a 25 mm$\times$120 μm line focus. The slab Ge targets about 2 mm thick, 3 mm wide, and 20 mm long were irradiated with the power density about 1.2×10^{13} W/cm^2.

The flat molybdenum-silicon multilayer mirrors were used at normal incidence to produce double-pass amplification of ASE from the gain medium, which consists of 15 pairs of layers with a period of 12.6 nm. The calculated reflectivity of the multilayer mirrors was about 15% at 23.2 nm.

The line intensities of the x-ray laser at 23.2 and 23.6 nm were measured with a flat-field grating spectrometer. In these experiments, record methods of time-integrated and time-resolved modes were used to measure the laser line intensities. Kodak 101-07 film was used in the time-integrated measurements and a streak camera was used in the time-resolved measurements. Both of them were behind the spectrometer. The slit of the streak camera was 100 μm wide and 16 mm long; the temporal resolution was about 50 ps.

The experimental arrangement is shown in Fig. 1. The slab Ge targets were mounted at the position of the line focus and the multilayer mirrors were 20 mm away (the distance could vary in the range 10–40 mm) from one end of the target. The angle between the normal to mir-

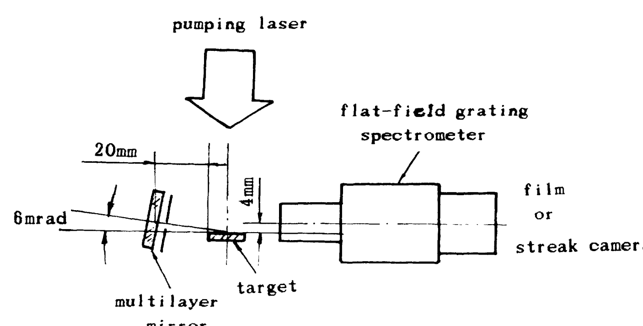

FIG. 1. Experimental setup.

ror and the plane of the target was 6 mrad and this angle could be adjusted in the 4–10 mrad range.

The flat-field grating spectrometer was 60 mm away from the other end of the target and 4 mm away from the target surface. The slit with the width of 15 μm was parallel to the optical laser beam. This arrangement was because of the angle offset of the x-ray laser refracted by the gain medium. The x-ray laser intensity of single-pass emission was measured without the mirror and that of double-pass emission was measured with the mirror.

III. EXPERIMENTAL RESULTS

A. Time-integrated results

By using the flat-field grating spectrometer with x-ray film Kodak 101-07, the intensities of the lasing lines at 23.2 and 23.6 nm were measured with or without the multilayer mirror. Two Al filter films (thickness 2×224 $\mu g/cm^2$) were used between the slit and the grating to get suitable film density to x-ray spectra. In order to optimize the mirror offset, a series of shots were carried out by varying the mirror angle from 5 to 10 mrad. The intensities of the double-pass signal were not obviously different from shot to shot, but the pointing directions of the main beam of the double-pass signal were variable if the mirror angle was changed from 5 to 8 mrad. However, the intensity decreased, and the pointing direction of the main beam was closer to the target surface if the mirror was at 10 mrad. Therefore we have chosen the angle to be 6 mrad in order to measure signal enhancement. The results of the two shots are shown in Fig. 2. One is the double-pass signal, the other is the single-pass signal. From Fig. 2 we see that the angle offset of the double-pass signal is slightly smaller than that of the single-pass signal. It is clear that the double-pass amplified signal is at least five times more intense than the single-pass signal. The integrated intensity ratio (double-pass to single-pass) is the same as the peak intensity ratio. The film densities of spectra were converted to intensities according to the response given by Eidmann [14].

B. Temporal resolution results

The temporal resolution signals of lasing lines were measured by using the flat-field grating spectrometer with the streak camera. The image converter tube of the streak camera matched an optical contact camera. The thickness of the Al filter film was varied with the lasing line intensity to get an explicit photograph. The temporal resolution signal of the single-pass emission is shown in Fig. 3. The continuum emission to x-ray laser emergence separation is about 200 ps and the x-ray laser duration (full width) is about 1 ns as the pulse width (FWHM) of the pumping laser is ~1 ns. Also, the beginning of the x-ray laser at 23.2 nm is slightly delayed, compared with that at 23.6 nm.

The temporal resolution signals of the double-pass

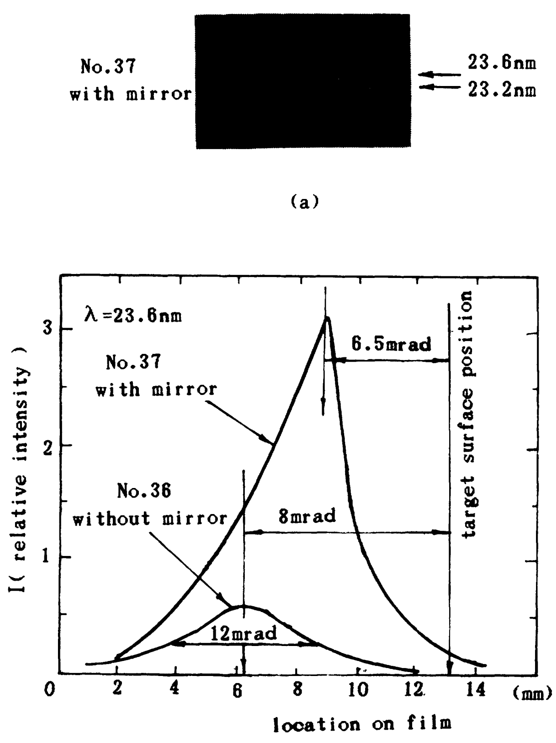

FIG. 2. Time-integrated results for shot nos. 36 and 37. (a) Time-integrated photograph of double-pass emission; (b) lasing line ($\lambda=23.6$ nm) intensity profiles in the no-dispersion direction.

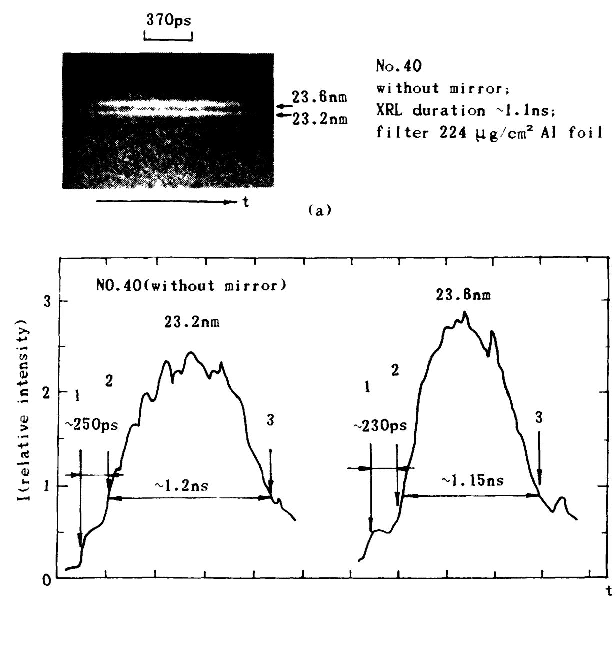

FIG. 3. Temporal resolution signals of the single-pass emission for shot no. 40. (a) Photograph obtained by streak camera; (b) line intensity vs time. 1, emergence of continuum emission; 2, XRL beginning; 3, end of XRL.

emission are shown in Fig. 4. The duration of the mirror operation is about 440 ps as the mirror distance from the target is 20 mm (shot no. 42) and about 700 ps as the mirror distance from the target is 30 mm (shot no. 46). The reason for the decrease in duration is that these multilayer mirrors were destroyed by the irradiation of laser plasma and the scattering pumping laser. Endurance issues are important because the multilayer mirrors must perform in a very hostile x-ray environment. The lifetime of a multilayer mirror in this environment requires experimental investigation. Gray *et al.* [15] have carried out the investigations, showing that the lifetime of the W-C multilayer mirror is about 1 ns if the irradiating flux of the x ray is 200 MW/cm^2. In addition, we have made the experimental measurement with the mirror distance at 10 mm, and no double-pass signal was observed. It is clear that the mirror is soon destroyed when the mirror distance is 10 mm. When the distance is 20 mm, the time-integrated enhancement given above is a factor of 5, but the actual time-resolved intensity enhancement is even larger because the laser with the mirror is enhanced only for part of the laser duration. Therefore it is necessary to improve the ability of the multilayer mirror against the radiation because the mirror must perform in a very hostile x-ray environment.

The time-integrated results showed that the signal enhancement factor (if it is a ratio of the peak intensity of the single-pass emission to that of the double-pass emission) could not be simply determined according to the time-resolved signal by a fixed streak camera, which is connected with the flat-field grating spectrometer as shown in Fig. 1, because the peak of the beam pattern moves when the mirror is used, as shown in Fig. 2. The time-resolved measurements involve a slit (about 100 μm width) that allows only part of the beam pattern to be visible, so it is not certain that the two peak signals (the single-pass and the double-pass emissions) were measured simultaneously. For example, when the slit of the streak camera is fixed on the peak position of the single-pass signal, the peak of the double-pass signal is not registered by the streak camera.

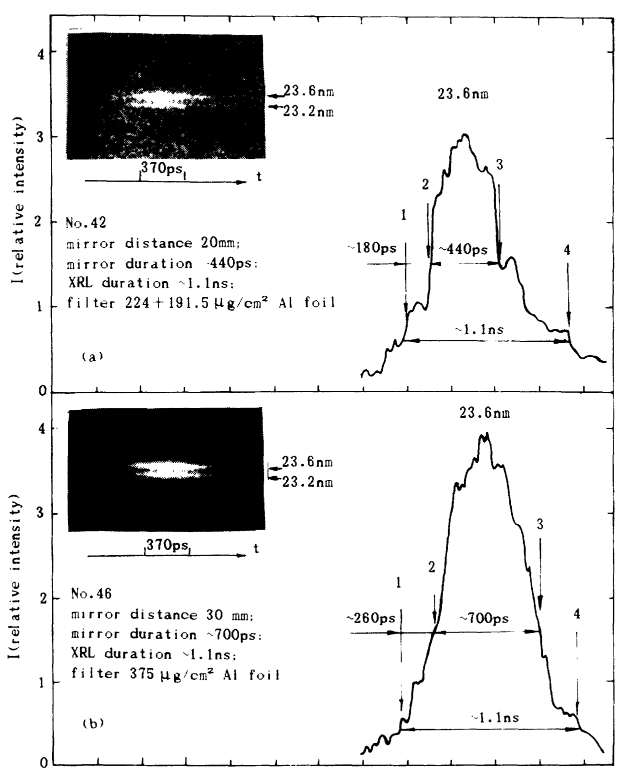

FIG. 4. Temporal resolution signals of the double-pass emission for shot nos. 42 and 46. (a) Mirror distance 20 mm; (b) mirror distance 30 mm. 1, XRL beginning; 2, occurrence of mirror reflection; 3, the mirror destroyed by irradiation; 4, end of XRL.

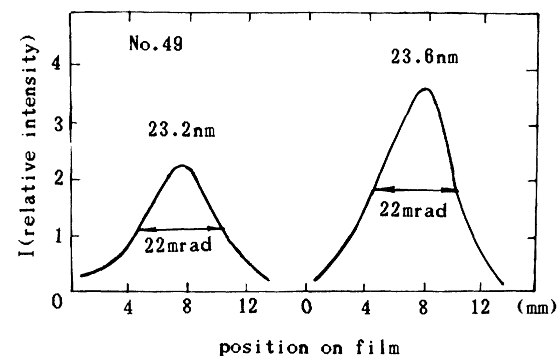

FIG. 5. XRL beam profiles of time-integrated measurements in the vertical direction for shot no. 49.

C. Beam optics characteristics of the x-ray laser

We have carried out the measurements of the x-ray laser beam optics in Ne-like Ge [16]. However, we have previously measured the beam optics characteristics only in the horizontal direction. In this paper, we have obtained the results of beam optics in the horizontal direction and in the vertical direction. The beam pattern in the vertical direction was measured by a grazing-incidence grating spectrometer, which was mounted at the vertical direction; that is, its slit was at right angles with that of the flat-field grating spectrometer. The main

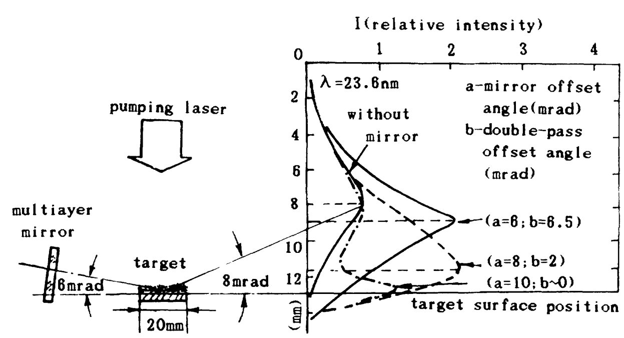

FIG. 6. Beam optics of double-pass amplification. It shows that four different time-integrated measurements of the beam pattern are made in the horizontal plane, one without a mirror and three with a mirror, mounted at the different mirror angles.

beam in the horizontal direction is seen to exhibit an angular divergence of 12 mrad with an offset 8 mrad from the plasma axis and the angular divergence in the vertical direction is about 22 mrad for a 20-mm-long plasma of 120 μm lateral dimension. The beam divergence in the vertical direction is shown in Fig. 5.

In addition, we have investigated the beam optics of the double-pass signal in the time-integrated measurements. The beam optics of the double-pass signal was given in Fig. 6. The pointing direction of the main beam of the double-pass emission is not the same as that of the single-pass emission, and it could vary with the displacement of the mirror. The larger the mirror angle is, the closer to the target surface the pointing direction of the main beam of the double-pass emission is. It is clear that the beam pointing direction could be adjusted with a mirror.

In a soft-x-ray laser, amplification is achieved as the x rays propagate down a long, narrow plasma column. Refraction [17] due to electron-density gradients tends to direct the x rays out of the high-density region. This affects the time-integrated beam pattern that is measured. On the other hand, our experimental results of the beam pattern have given some information of electron-density gradients of the gain medium. From Fig. 6, it is seen that the intensities of double-pass signals are not obviously different from shot to shot as the mirror angle is varied from 6 to 8 mrad. This means that there is a homogeneous gain region in the gain medium, this region is not far away from the target surface, and the gain coefficient approximates to a constant in the region. The signal intensity decreases as the mirror angle is at 10 mrad because x rays reflected by the mirror enter into the high-density region close to the target surface and the gain coefficient is small in the region.

IV. CONCLUSION

The double-pass amplification of the x-ray laser in neonlike Ge was demonstrated successfully. The enhancement by more than five times of the time-integrated double-pass signal was observed. The lifetime of the multilayer mirror was 440–700 ps in these experiments. It is necessary that a good quality multilayer mirror be fabricated in order to obtain the multipass amplification of the x-ray laser with an x-ray laser (XRL) cavity in a very hostile plasma environment. Ceglio's [11] results and ours show that the enhancement of the double-pass signal is less than expected. The reason is not yet clear and future experimental investigations are necessary.

ACKNOWLEDGMENTS

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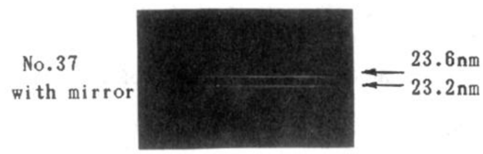
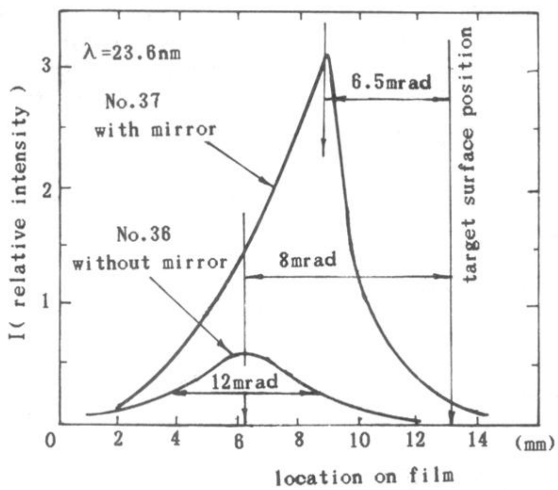


(a)



(b)

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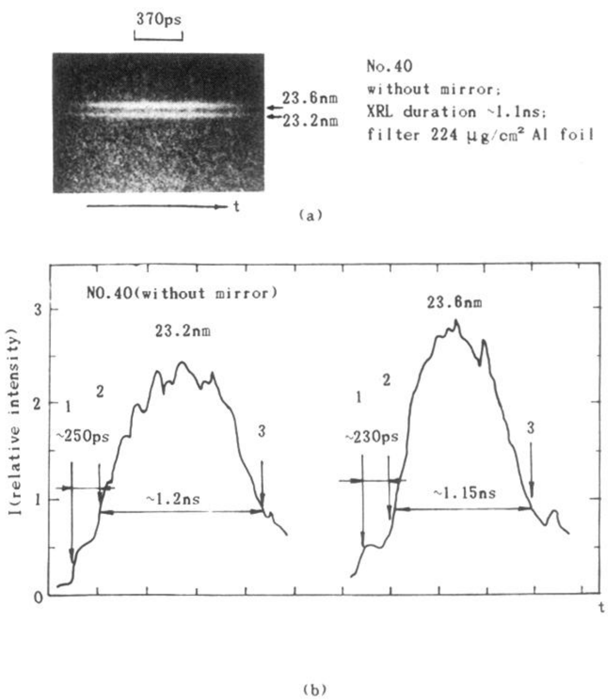

FIG. 3. Temporal resolution signals of the single-pass emission for shot no. 40. (a) Photograph obtained by streak camera; (b) line intensity vs time. 1, emergence of continuum emission; 2, XRL beginning; 3, end of XRL.

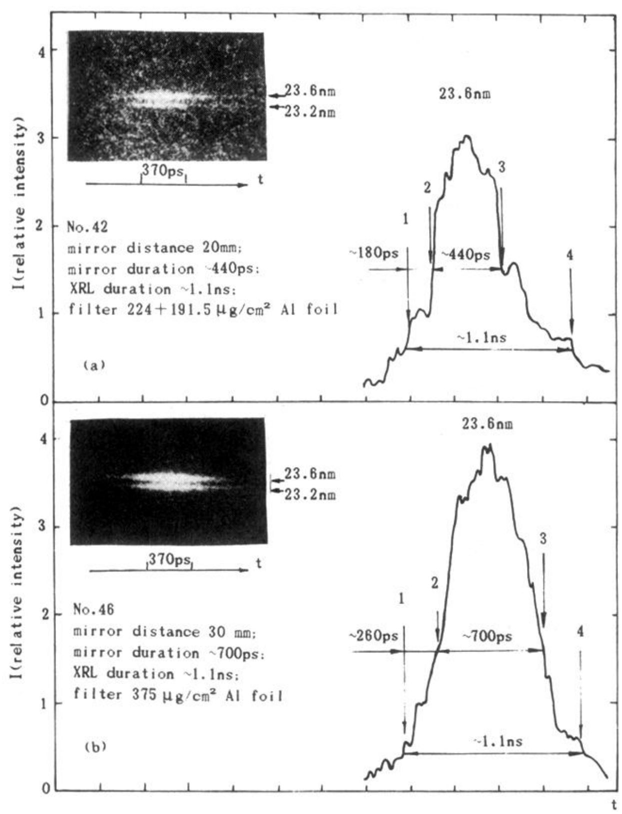

FIG. 4. Temporal resolution signals of the double-pass emission for shot nos. 42 and 46. (a) Mirror distance 20 mm; (b) mirror distance 30 mm. 1, XRL beginning; 2, occurrence of mirror reflection; 3, the mirror destroyed by irradiation; 4, end of XRL.