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Experiment of Si target ablation with soft X-ray laser operating at a wavelength of 46.9 nm

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ABSTRACT

We successfully ablated the Si target by the focused beam of capillary-discharge pumped laser at 46.9 nm. The laser of $\sim$50 μJ was focused by the sagittal surface of the cylinder mirror at grazing incidence. Fluences of the focused beam were varied by changing the distance between the mirror and target, and clear ablation patterns were obtained. The shapes of the patterns were consistent with the results simulated by ZEMAX software. The irradiance of the focal spot was simulated as well. Each pattern was ablated by 200 shots and the sampling distance between any two contiguous ablation positions was 0.7 cm. The peak value of energy density of the focal spot was estimated to be 7.48×10^{-3} J/cm^2. According to the ablation pattern, the focal point of the mirror was determined. The experiment provides reliable data and focusing method for interaction of X-ray laser with solid target.

1. Introduction

As a kind of laser with short wavelength, soft X-ray laser has a bright development foreground in the field of laser application such as plasma diagnostic technique, photolithography and detection in the environment of living cells and so on. After the demonstration of soft X-ray laser at 46.9 nm pumped by capillary discharge as the forth team in the world [1], our group expands the ablation experiment about interaction of X-ray laser with solid target.

Based on the prospect of X-ray laser application and tendency of miniaturization of instrument, many experts made ablation experiments with X-ray laser pumped by capillary discharge. The American team of Rocca made the most successful result [2]. Cu target was ablated with focal X-ray laser in 1999. Images of the ablation patterns were clearly showed in the focal region. Cross section of the beam was also calculated in the focal region. Then the team ablated a spherical Si/Sc multilayer mirror with three fluence of 0.13 J/cm^2, 1.5 J/cm^2 and 2.8 J/cm^2 in 2003 [3], obtaining ablation pattern and ablation depth. The damage threshold and damage mechanisms were also investigated in Sc/Si multilayer EUV mirrors. Two years later Rocca's team made nanometer-scale ablation with the same laser beam [4]. The hole with 82 nm diameter and 250 nm depth was achieved in the nickel sample. There are also some other experiments about the interaction of capillary discharged X-ray laser at 46.9 nm with solid target. Juha's team from Czech researched the interaction of X-ray laser with amorphous carbon thin films in 2009 [5]. The experiment was operated below the single-shot damage threshold of the carbon. The experimental result demonstrated that XUV-laser radiation can damage a-C layers exposed to tens of shots at a fluence of about half the single-shot damage threshold. Ritucci's team of Italy [6] ablated the surfaces of dielectrics with ul-tralarge bandgaps and obtained clear craters at different fluences. The experiments above show the essentiality of focal X-ray laser and ablation with solid target because of the foreground in the field of X-ray laser application.

X-ray laser is not focused easily with the way of transmission, as it is easily attenuated by material. All the above experiments used multi-layer mirror to focus the X-ray laser at the normal incidence. This focus method can be used to minimize the optical aberration and optimize the focal spot, which means the peak intensity of focused laser beam is quite high and the ablation pattern is in high precision. However, this method has its drawbacks as well. The technology about the multi-layer on the mirror is difficult to operate. And the high fluence will damage the multi-layer and reduce the reflectivity. At the same time, the ejecting debris from the capillary wall and electrodes ablation will bombard the optical element and inflect the focal effectiveness.

Grazing incidence is able to solve the problems above. The mirror's focal distances of sagittal surface and meridian plane are

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calculated using the following formulas [7]:

$$f_s = \frac{R_s}{2\cos i_s} \quad (1)$$

$$f_m = \frac{R_m \cos i_m}{2} \quad (2)$$

where f_s, R_s and i_s are the focal distance, curvature and the incidence angle of sagittal surface. f_m, R_m and i_m are the corresponding parameters of meridian plane. It shows that if the parameters of sagittal surface and meridian plane are equal, as a spherical mirror does, f_s is not equal with f_m. That means the spherical mirror could not focus X-ray laser effectively in the grazing incidence way.

Based on the analysis above, cylinder mirror was used in the grazing incidence way in our experiment. Then we successfully focused X-ray laser. There was no multi-layer on the cylinder mirror and the damage of optical elements from incident beam was reduced because of the lower fluence. The reflectivity in this condition is alomost 90% at the incidence angle of $\sim 90^\circ$ [8] which is much higher than the reflectivity of 30%–40% by normal incidence. This method also has its weakness. The optical aberration due to the large incidence angle limited the beam's focus ability. Therefore, the shape of focal spot is not as good as the one obtained by normal incidence. This method can be used to ablate large regions. For instance, the method can be used to focus the X-ray laser beam to radiate cluster, gas or plasma. What is more, this method can be used to focus multi-wavelength lasers. Our team has already achieved the laser beam at a multi-wavelength of 46.9 nm and 69.8 nm [9].

2. Experimental setup

The optical source of this equipment was X-ray laser at 46.9 nm with the pulse width of 1.7 ns. It was a beam from 35 cm-long Ar capillary plasma that was excited with a fast current pulse. The energy of every single pulse was about 50 μJ. The detail of the X-ray laser has been described in Ref. [10,11].

The vacuum chamber was used to provide the experiment environment at length of 106.5 cm, width of 66.4 cm and depth of 67.3 cm. In the experiment, the pressure in chamber kept about 10^{-4} Pa. The cylindrical mirror made of fused silica was used in the experiment to focus the X-ray laser. The curvature of meridian plane was zero and the curvature of sagittal surface was 4.76 cm. And there was no coating on the surface.

The focus beam path is showed in Fig. 1. The mirror was fixed at the bottom of the chamber. The X-ray diode was used to measure the laser signal. The X-ray diode and Si target were fixed on the translation stage to keep relative still. The axis of motion of translation stage was positioned at an angle of 45° with respect to the optical axis. When the stage moves on one dimension, the target and the X-ray diode could move on two-dimension. By moving the target along the optical axis of mirror we changed the fluences of the focused beam. According to the curvature of the mirror and the incidence angle of 83°, we calculated $f_s = 19.51$cm with the formula (1). The Si target was positioned around the site of the theoretical focal point, and the beam path was simulated by a He–Ne laser. The stage was moved to determine the ablating position on the target. The focal beam was irradiating on the X-ray diode or the Si target while the stage moved.

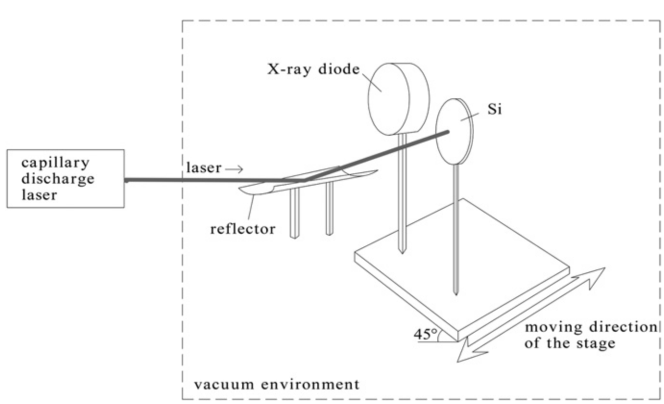

Fig. 1. Focus beam path of X-ray laser.

3. Experimental results and analysis

3.1. Measurement results of laser signal

First the unfocused laser signal was measured. X-ray laser at 46.9 nm irradiated on the cathode of the X-ray diode. The oscilloscope captured the laser signal showed in Fig. 2. A slit was used to scan the incidence spot at the position of the cylindrical mirror. The X-ray diode was used to detect the variation of the laser energy. Fig. 3 is the variation of laser energy at the position of the mirror. The diameter of the spot was measured to be about 9 mm and the laser was determined to be Gaussian-like. The detected data of the spot was used to simulate the shape and energy density of the focal spot. After the cylindrical mirror was positioned in the beam path, the focal laser signal was detected by the X-ray diode. Compared the focal laser signal with unfocused one, the reflectivity of the cylindrical mirror was computed to be more than 90%.

Since the laser was generated by pumping Ar capillary plasma, the fluxion of gas can affect the stability of laser. The added vacuum chamber affected the fluxion environment of laser, which also varied the stability of laser pulses. We developed the gas filling system etc to increase the output energy stability of laser. After the steady laser was measured with the X-ray diode, the Si target was moved into the beam path while the X-ray diode was moved out of the beam path. Then the focal laser was used to ablate the Si target and make ablation pattern.

3.2. Theoretical simulation and experimental results

Based on the data of the beam path and the measured result of the incidence spot, we used ZEMAX software to simulate the

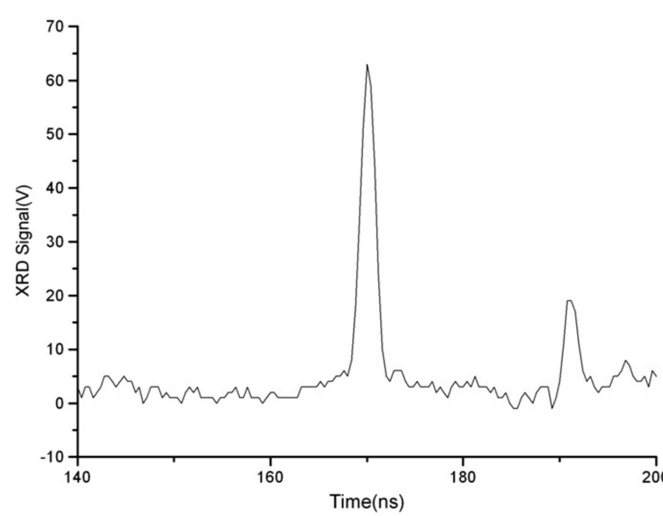

Fig. 2. Signal of X-ray laser in the experiment.