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Modulations of the plasma scald on the downstream beam

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ABSTRACT

The plasma scald damage is the most typical laser damage morphology presented on the laser conditioned HfO_2/SiO_2 mirrors. In order to provide guidance for defining the acceptance quantitative specification for the plasma scald on these laser conditioned mirrors, the simulations about the downstream beam modulations of the plasma scald are investigated based on its damage characteristics and the diffraction theory. The single plasma scald with the typical size, induced by the laser conditioning, can hardly cause damage to the downstream optics and its influence on the beam contrast can be reduced easily with the increment of the propagation distance. Those with small size and large depth, or those with big size and shallow depth can also hardly induce downstream damage, but the beam contrasts become worse with the increment of the size of the concave part as well as its depth. For a maximum plasma scald observed on the laser conditioned mirror, the intensity modulation peak is close to 1.3 and the beam contrast reaches to 25% even at 2 m downstream from the mirror. For multi plasma scalds, more diffraction rings show up in the downstream beam and further decrease the overall uniformity of the beam. The uniformity of the beam gets worse as the number of the plasma scald is increased. When the density of the plasma scald with the typical size in these $1\omega HfO_2/SiO_2$ mirrors reaches 20 per 1 cm^2, the beam contrast is less than 6%.

1. Introduction

Raster-scan laser conditioning is an effective technology to improve the laser damage resistance of $1\omega HfO_2/SiO_2$ mirrors, which are used in high power laser systems [1–4]. After being conditioned by nanosecond laser pulses with a wavelength of 1064 nm, plasma scald damage is the most typical damage morphology presented on these mirrors [3–8]. This damage, induced by laser conditioning, is allowable on the optics owing to its benign damage characteristics, such as stability, shallow damage depth, little influences on the roughness and spectrum of the optics [9–13]. The plasma scald measured with the Zygo GPI-XP phase modulating interferometer presented a negative phase modulation [9], which indicates that it can be simply modeled as a concave lens and acts as a neglectable weak scatter site. Unfortunately, the experimental measurement indicated that plasma scalds could lead to fratricide of downstream optics by increasing beam contrast. Plasma scald fractions of 4% and below were measured to contribute a contrast adder of less than 2.5% [14]. It was reported that mirrors with plasma scald fractions greater than 3% were not used on National Ignition Facility (NIF) [4]. However, the acceptance quantitative specification for the plasma scalds on the laser conditioned $1\omega HfO_2/SiO_2$ multilayer mirrors, which is determined by their influences on the downstream beam, is still indistinct by now. The influence of the plasma scald damage on the downstream beam depends on the propagation distance of the downstream beam, the scalding degrees as well as the scalding density.

To further understand the impact of the plasma scald on the downstream beam, this paper focuses on the simulations about the downstream modulations due to the plasma scald based on its damage characteristics. First, the modulations of the plasma scald with the typical size at the different downstream positions are studied. After that, the modulations of plasma scalds with different lateral sizes and depths on the downstream beam are investigated. At last, the modulations induced by multi-scalds in the beam aperture are simulated. The purpose is to evaluate the influence of the plasma scald on the downstream beam quality. These results, which can provide guidance for defining the acceptance quantitative specification for the plasma scald on the laser conditioned $1\omega HfO_2/SiO_2$ multilayer mirrors, are required for laser

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conditioning work.

2. Modulation theory and model based on the characteristics of the plasma scald

The modulation effect can be derived from the wavefront interaction between the incident beam and the damage site.Considering the downstream beam intensity enhancement is generated by the diffraction of the plasma scald, Huygens–Fresnel diffraction integral is applied for the simulations. The propagation distances are longer enough than the beam aperture in our calculations, so each location on the whole downstream plane is paraxial. Under paraxial approximation, the downstream beam $E(x_2, y_2, z)$ could be expressed as [15]:

$$E(x_2, y_2, z) = \left(-\frac{i}{\lambda z}\right)\exp(ikz) \iint_s E_0(x_1, y_1, z)\cdot t(x_1, y_1)\exp\left\{\frac{ik}{2z}\left[(x_2 - x_1)^2 + \left(y_2 - y_1\right)^2\right]\right\}dx_1\,dy_1$$

where $E_0(x_1, y_1, z)$ is the incident beam, $t(x_1, y_1)$ is the modulation factor induced by the plasma scald, (x_1, y_1) represents the space coordinate on the mirror plane,and (x_2, y_2) represents the space coordinate on the downstream plane. Fig. 1 shows the incident beam and its propagation.

Here, the incident beam is chosen as super-Gaussian beam which is the same as the incident beam in the high power laser system, such as NIF, the Laser Megajoule (LMJ), SG and so on. Thus super-Gaussian beam [16] is taken into calculation and the incident beam at the plane of $z=0$ can be written as.

$$E_0(x_1, y_1, z = 0) = \exp\left[-\left(\frac{|x_1|}{\omega_0}\right)^N - \left(\frac{|y_1|}{\omega_0}\right)^N\right]$$

where N denotes the beam order and ω_0 is the waist width.

Plasma scalds on the mirrors were proved to make little influence on the spectrum of the mirrors [9], so the plasma scald can only be considered as a phase modulation factor when the incident beam interacts with it. Considering the reflection of the mirror, this local phase modulation function on the downstream beam is given by

$$t(x_1, y_1, z = 0) = \exp\left[i\phi\left(x_1, y_1, z\right)\right] = \exp\left(i\frac{4\pi}{\lambda}h\right)$$

where h is the depth ($h < 0$) or height ($h > 0$) of the surface of the plasma scald damage relative to the undamaged film surface.

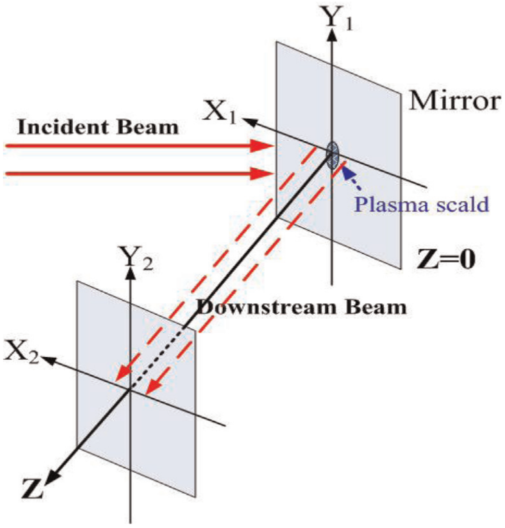

Fig. 1. Schematic diagram of the incident beam and propagation.

The statistical result shows that all the scalds on the conditioned mirrors exhibit the same damage characteristics. Scalding behaves as surface discoloration under microscope as shown in Fig. 2(a). Its step profile micrgram illustrated by Fig. 2(b) indicates that the periphery of the scalding is convex and the center region is concave. Based on this fact, the simplified model of the plasma scald in Fig. 2(c) is used. Here, the surface shape of scalding is assumed to be circular and centrosymmetric. Besides that, the concave region is regarded as a spherical cap, and the convex periphery is considered to be formed by the rotation of another small spherical cap around the symmetry axis. The differences in downstream modulations, induced by the little differences in geometry between the idea model in Fig. 2(c) and the realistic profile in Fig. 2(b), is small and can be ignored. According to the model in Fig. 2(c), the depth ($h < 0$) or height ($h > 0$) of the scalding can be written as follows:

$$\begin{aligned} h &= h_2 - r_2 + \sqrt{R_2^2 - (r_1 + r_2 - x_1)^2} && (r_1 \le x_1 \le 2r_2 + r_1) \\ h &= -\left(h_1 - r_1 + \sqrt{R_1^2 - x_1^2}\right) && (-r_1 \le x_1 \le r_1) \\ h &= h_2 - r_2 + \sqrt{R_2^2 - (r_1 + r_2 + x_1)^2} && (-2r_2 - r_1 \le x_1 \le -r_1) \end{aligned}$$

where $R_1 = \frac{\sqrt{r_1^2 + h_1^2}}{2h_1}$,$R_2 = \frac{\sqrt{r_2^2 + h_2^2}}{2h_2}$,$r_1$ is the radius of the concave part, h_1 is the maximum depth of the concave part, r_2 is the radius of the convex part, and h_2 is the maximum height of the convex part, respectively.

Besides the intensity modulation, the beam contrast, which characterizes the overall quality/non uniformity in the intensity profile of the laser beam and is defined as the standard deviation of the light intensity divided by its mean value [17,18], is also calculated. The beam contrast is required to estimate because it is related to the safety of the laser system, as well as the final output energy. The beam contrast can be written as.

$$\text{Beam contrast} = \sqrt{\frac{1}{nm}\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{F\left(x_i, y_j\right) - \bar{F}}{\bar{F}}\right)^2}$$

where $F\left(x_i, y_j\right)$ is the pixelated light intensity, $\bar{F}$ is the average light intensity in the beam aperture, m and n is the number of total pixels in the line and column, respectively.

3. Results and discussions

The wavelength of the incident beam is 1.053 µm.The waist width ω_0 is chosen as 1 cm and the beam order N is chosen as 10 in our paper.When the laser interacts with the plasma scalding damage, diffraction rings are shown up in the downstream beam as that can be seen in Fig. 3. The light intensity values along the line in Fig. 3 are chosen to describe the intensity modulation of the downstream beam in our paper.

3.1. The influence of the propagation distance on the downstream beam modulation induced by the typical plasma scald

The statistical distribution of the radius of the concave part r_1, in the laser conditioned mirrors is given by Fig. 4. The typical radius of the concave part r_1 is about 150 µm, and its corresponding depth h_2 is about 35 nm proved Ref. [11], just as Fig. 2(b) shown.