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Analysis on wavefront modulation by PSD*

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Abstract: The power spectral density (PSD) has been employed as the specifying parameter of the optical components with large aperture in the testing process. According to the different wavefront modulation with different depth or frequency, the PSD curves present different variation rule. The change of the modulation frequency will change the corresponding frequency value of the protuberant part on the PSD curve, and at the same time the peak value of the protuberant part is changed. The modulation depth is focused on the intensity change of the protuberant part of the PSD curves. It cannot influence the frequency value of the protuberant part.

Key words: Power spectral density; Wavefront modulation; Modulation depth; Modulation frequency

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At present, the wavefront-testing technique of the optical components, which is the guarantee of the system's safe and efficient function, has been a very important part of the high-power laser system. For example, in the inertial confinement fusion (ICF) drive system, self-focusing is one of the most important damage factors of the optical components[1,2]. The main causation of the self-focusing is the distortion of the wavefront, which will cause the nonlinear process in the nonlinear medium. In laser system, the distortion of the wavefront is caused by the modulation from the surface of the components.

On the other hand, testing the surface of all the components is a right way to guide the fabrication, while precise fabrication will reduce the errors of the wavefront. In application, transmitted wavefront errors can be divided into 3 spatial frequency regimes[3,4]: figure, ripple and roughness. Different error regime need different fabrication manner. So it is necessary to know the particular wavefront information of the components.

Power spectral density (PSD) is one kind of the Fourier techniques to characterize the wavefront. It can be related to the spatial frequency regimes of the wevfront errors. PSD is widely used[3~5] in high-power laser systems. In this paper, PSD is employed as the specifying parameter to analyze the characteristics of different modulation. This method can show the relationship of the testing results and the fabrication process more directly.

1 Groundwork

In ICF drive system, the laser beam with plane wavefront was used mostly. In this paper, we use a super-Gauss function to simulate an ideal plane wavefront, just as the following,

$$\Phi(x) = 200\mathrm{e}^{-\pi\left(\frac{x}{10}\right)^{30}} \tag{1}$$

where x is the coordinates of the phase distribution in one dimension. Using Eq. (1) we can describe the phase of the wavefront with about 200nm phase height and 20mm diameter wide, as shown in Fig. 1. The calculation of the PSD is based on the Fourier transform technique. The calculation formula of the PSD has such form as[6,7]

$$P(f) = \frac{\Delta x}{N} \left| \sum_{n=0}^{N-1} \Phi(x)\mathrm{e}^{-2\pi \mathrm{i} nfx} \right|^2 \tag{2}$$

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where f is the spatial frequency, $\Phi(x)$ is the phase distribution function, N and Δx are the total number and the interval of the sample point respectively, and here $\Delta x = 0.5\text{mm}$[8]. Using Eq. (2) the PSD curve of the plane phase distribution can be calculated by substituting Eq. 1 into Eq. (2). The curve is shown in Fig. 2.

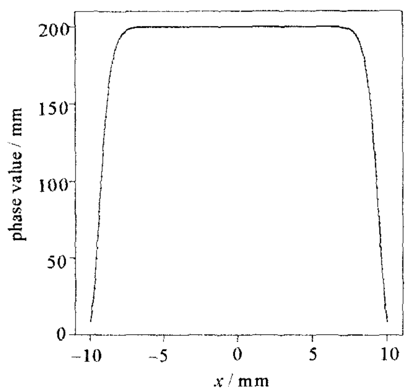

Fig. 1 Phase distribution of the ideal wavefront

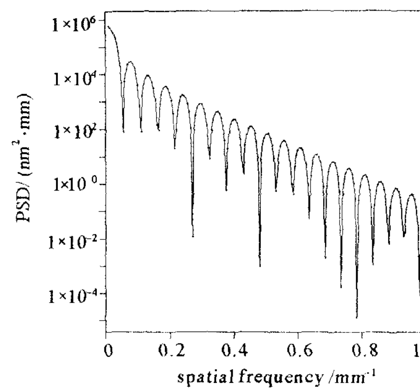

Fig. 2 PSD calculation result of the ideal wavefront

From Fig. 1 and 2, we know that the ideal phase distribution should be a smooth and gradually changed curve. After propagates through the optical components, the phase distribution of the wavefront will be distorted. Because the components' surface will influence the wavefront by the effects such as scatter, diffraction and so on. To keep track of the rule of the modulation results and also for easy discussion, we use the modulation with sine-shaped form. The phase distribution can be described as

$$\Phi(x) = 200e^{-\pi(\frac{x}{10})^{30}} e^{M\sin(I\pi x)} \tag{3}$$

where I is the parameter relevant to the modulation frequency, and M is the parameter relevant to the modulation depth. Using Eq. (3), we get the different modulations on the wavefront by changing the value of I or M. On substituting Eq. (3) into Eq. (2) we can get

$$P(f) = \frac{\Delta x}{N} \left| 200 \sum e^{-\pi(\frac{x}{10})^{30}} e^{M\sin(I\pi x)} e^{-2\pi nf} \right|^2 \tag{4}$$

And different I or M will cause different PSD curves.

2 Calculated results for different modulation frequencies

As an effective testing parameter, PSD differs greatly from the usual P-V and RMS. The outstanding merit of the PSD is that it can give the direct relationship of the modulation frequency and the phase distribution. In this paper, we use the modulation with sine-shaped form to discuss different PSD with different modulation frequency. Using Eq. (4), we can get different phase distributions with different frequencies by changing I and keeping M unchanged. The range of the frequency is from 1π to 6π with random interval and the modulation depth is 0.01nm. Fig. 3 shows the phase distribution with 2π modulation frequency. Fig. 4～6 are typical calculation results of the PSD curves with different modulation frequency.

Fig. 4～6 show that when the phase distribution is distorted, there will be a protuberant part on the PSD curve. Along with the increasing of the modulation frequency, the corresponding frequency of the protuberant part increases. With 2π, 4π and 5π modulation frequencies the spatial frequency of the protuberant part are 0.33, 0.68 and 0.81mm^{-1}, respectively. It can also be seen from Fig. 4～6 that the PSD peak value is constant for different modulation frequency. In fact, the protuberant parts have the same PSD peak value of 108.5$\text{nm}^2 \cdot \text{mm}$ for all the frequencies. The frequency at the protuberant parts is determined by the surface quality of the optic components so if we get the PSD analysis result of any optical component, it can be found out that the elementary information of the fabrication error.

3 Calculated results for different modulation depth

Using Eq. (4) different phase distributions with different modulation depths can be calculated by changing M

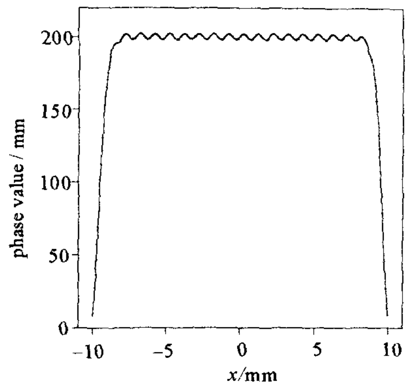

Fig. 3 Phase distribution with 2π modulation frequency and 0.01nm modulation depth

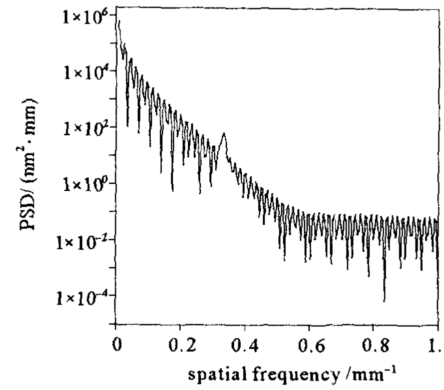

Fig. 4 PSD curve of the phase distribution with 2π

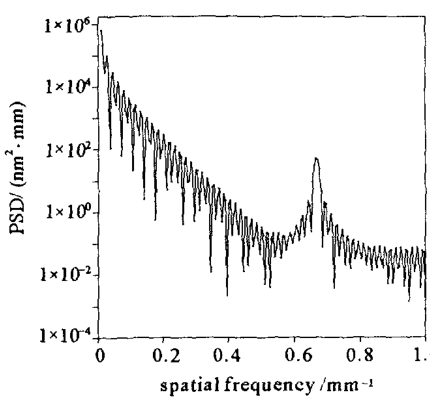

Fig. 5 PSD curve of the phase distribution with 4π modulation frequency

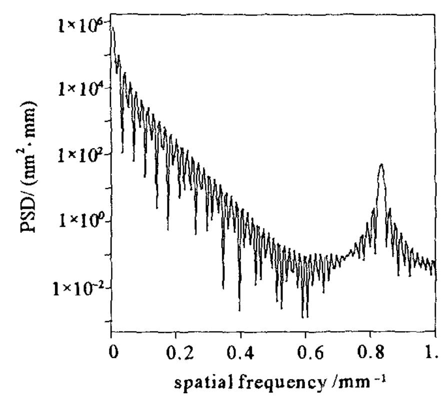

Fig. 6 PSD curve of the phase distribution with 5π modulation frequency

and keeping I constant. In the calculation, the modulation frequency is 4π and the range of the modulation depth is from 0.1nm to 0.000 5nm with random interval. Fig. 7 is the phase distribution with 4π modulation frequency and 0.1nm modulation depth. Fig. 8~10 are typical results of the PSD curves with the modulation depth of 0.1nm, 0.001 8nm, respectively.

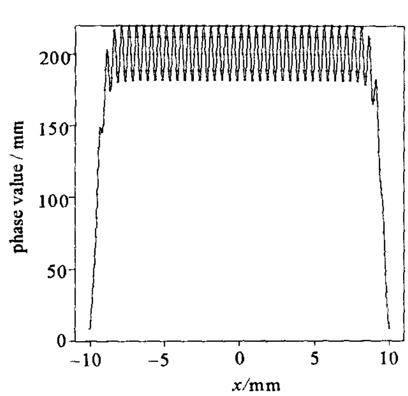

Fig. 7 Phase distribution with 4π modulation frequency and 0.1nm modulation depth

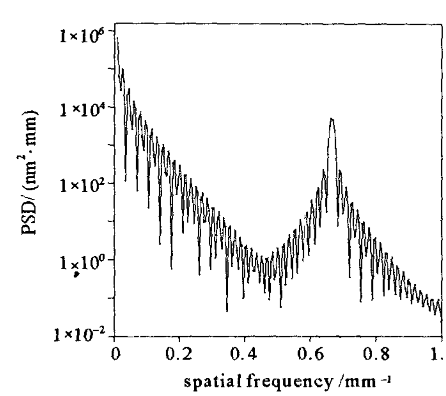

Fig. 8 PSD curve of the phase distribution with 0.1nm modulation depth

Fig. 8~10 show various PSD peak values. The PSD values of the peaks are 10 840, 108.5 and 4.29nm^2 · mm, for the modulation depth of 0.1nm, 0.01nm and 0.001 8nm, respectively. However, the spatial frequency of the protuberant part keeps unchanged at 0.68mm^{-1}. So it can be concluded that the affection of the modulation depth is focused on the intensity change of the protuberant part of the PSD curves.

4 Conclusion

In this paper, we discuss the phase distortion of the wavefront by the PSD analysis. When the modulation depth is unchanged, the change of the modulation frequency will change the corresponding frequency value of the protuberant part on the PSD curve. The frequency of the protuberant part increases with the increasing of the modulation frequency, and the peak value is unchanged. When the modulation frequency is unchanged, the fre-

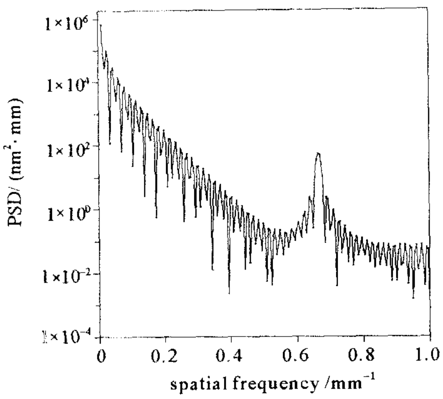

Fig. 9 PSD curve of the phase distribution with 0.01nm modulation depth

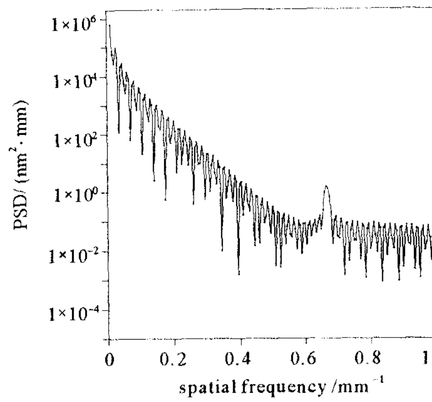

Fig. 10 PSD curve of the phase distribution with 0.001 8nm modulation depth.

quency of the protuberant part of the PSD curve is unchanged. But the peak value of the protuberant part changes with the modulation depth. Deeper modulation will cause higher peak value. The results obtained here will be useful on the test of the optical components. In PSD anylysis, we can get the wavefront modulation information from the protuberant part on the PSD curve.

References :

[1] Xu Q, Gu Y Y, Cai L, et al. The calibration of the system transfer function for large interferometer. *High Power Laser and Particle Beams*, 2001, **13**(3):321—324.

[2] Asadchikov V E, Duparre A, Jakobs S, et al. Comparative study of the roughness of optical surfaces and thin films by use of X-ray scattering and atomic force microscopy[J]. *Applied Optics*, 1999, **35**(4):684—691.

[3] Aikens D M, Wolfe C R, Lawson J K. The use of power spectral density (PSD) functions in specifying optics for the national ignition facility[A]. Proc of SPIE[C]. 1995, **2576**:281—292.

[4] Lawson J K, Wolfe C R, Manes K R, et al. Specification of optical components using the power spectral density function[A]. Proc of SPIE[C]. 1995, **2536**:38—50.

[5] Lawson J K, Aikens D M, English R E, et al. Power spectral density specifications for high-power laser systems[A]. Proc of SPIE[C]. 1996, **2775**:345—356.

[6] Zhang R. Z, Xu Q, Gu Y Y, et al. Testing errors and its influence of the large aperture optical components. *High Power Laser and Particle Beams*, 2001, **13**(2):133—136.

[7] Zhang R Z, Cai B W, Yang C L, et al. Numerical method of the power spectral density. *High Power Laser and Particle Beams*, 2000, **12**(6):661—664.

[8] Zhang R Z, Cai B W, Yang C L, et al. Calculation of the power spectral density of the wavefront[A]. Proc of SPIE[C]. 2000, **4231**:295.

大口径光学元件波前调制 PSD 模拟分析

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摘 要： 使用 PSD 作为大口径光学元件表面加工质量的评价参数,针对不同的波前调制进行了初步的模拟计算,得到了不同调制频率和不同调制深度情况下的 PSD 曲线变化情况。当调制频率不同时,PSD 曲线的突变部分会发生相应的频移,调制频率高则突变发生在空间频率较高的频段,同时 PSD 峰值不变。相对应调制深度不同时,PSD 曲线的突变部份峰值发生变化,调制深度大则峰值大,与此同时峰值出现的位置不会发生变化。计算和分析结果表明 PSD 分析结果能够在频率域反应出元件表面受到的不同程度的调制信息。

关键词： PSD 曲线； 波前调制； 调制深度； 调制频率