Laser beam smoothing based on spherical circular grating

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We propose a new method of beam smoothing based on spherical circular grating to reduce the perturbation in near field and focal plane. Our numerical simulation demonstrates that the smoothing effect using circular grating is better than that of 2D-SSD. The new method has potential application in inertial confinement fusion (ICF).

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1. Introduction

In laser heat and laser fusion processing, such as laser welding, cutting, heat treatments, and even Inertial Confinement Fusion (ICF), uniform illumination on the target surface must be required. However, many external factors, such as fabrication errors of the elements, lead to random phase modulation of the laser wavefront. The random phase modulation causes phase noise and affects the beam quality. In order to get a uniform intensity distribution, a beam smoothing technique must be introduced into the system.

Uniform irradiation on target plane is an essential issue in Inertial Confinement Fusion (ICF). Various beam-smoothing technologies have been proposed to improve laser irradiation uniformity on the target plane [1−6]. These technologies can be summarized into two categories. The first one is that the spatial smoothing approach of breaking the beam up spatially into fine-scale structure, including random phase plate (RPP) [1], continuous phase plate (CPP) [2], and lens array (LA) [3], etc. Second, the temporal smoothing approach that leads the structure to change rapidly with time and giving the beam with time-averaged smoothness includes induced spatial incoherence (ISI) [4] and smoothed by spectral dispersion (SSD) [5], etc.

The high-contrast speckle pattern generated by multiple random interferences between beamlets leads to Rayleigh–Taylor instability [6] when only spatial smoothing approach is used in ICF. So SSD technology is also adopted by ICF projects besides spatial smoothing approach. But widely used two-dimensional SSD (2D-SSD) method in ICF engineering only provide two-direction dispersion, thus beam intensity in other directions on focal plane is not fully smoothed, which is also raise the possibility of Rayleigh–Taylor instability. Although three-directional SSD (3D-SSD) was proposed, and it works better than 2D-SSD [13], its complexity and inconvenient adjustment prevent its application in Engineering.

In this paper, spherical circular grating is introduced to generate angular dispersion to improve the irradiation uniformity and simplify the whole ICF system. Chirp pulse beam is used as incident light and its propagation is analyzed after grating theoretically. Then, smoothing effect between spherical circular grating and linear grating are numerical simulated and compared. The result demonstrates that our numerical simulation demonstrates that the smoothing effect using circular grating is better than that of 2D-SSD. The new method has potential application in inertial confinement fusion (ICF).

2. Structure of spherical circular grating

Spherical circular grating is composed of series of concentric circles on a spherical surface, as shown in Fig. 1(a). Its period is constant viewed at diameter direction in Fig. 1(b). The steps between concentric circles and spherical surface ensure that the incident beam perpendicular to spherical circular grating at Littrow angle.

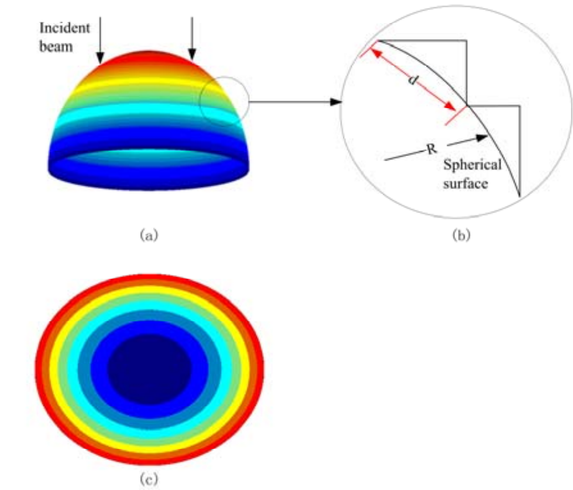


Fig. 1 Schematic of spherical circular grating, (a) bird's eye view, (b) side view, here d is the grating period, (c) vertical view.

In Fig. 2, we present principle of ICF research system, our grating located between pre-amplifier and main amplifier to provide spectral dispersion, where spherical circular grating is transmission-type.

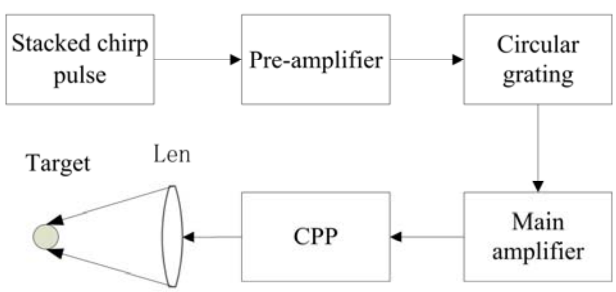


Fig. 2 Principle of ICF research system.

3. Theory of chirp pulse dispersion

The incident chirp pulse light can be described as follow [7].

$$E(t)=\sum_{k=0}^{n}E(x,y)\alpha_k \exp\left[-\frac{(t-krT_{FWHM})^{2m}}{2\tau^{2m}}-iC\frac{(t-krT_{FWHM})^{2m}}{2\tau^{2m}}\right]e^{-i\omega_0(t-krT_{FWHM})} \quad (1)$$

Where α_k is coefficient, $T_{FWHM}=2\tau(\ln 2)^{1/2m}$ is the full width at half maximum (FWHM), τ is half-width of e^{-1} intensity, $C=\Delta\omega/2$ is chirp parameter and r is overlap factor. Here τ=50ps and m=1 for Gaussian beam.

When stacked chirp pulse beam incidence at Littrow angle [8, 9] as Fig. 1(b) demonstrates, the value of dispersion is not easy calculated, but from Fig. 1(c), spherical circular grating can be viewed as plane circular grating when neglecting different time delays at different incident points, which makes dispersion calculation much easier. We use grating equation on the Littrow condition $2d\sin\theta=\lambda$, and then the angular dispersion introduced by spherical circular grating is:

$$\xi=\frac{\Delta\theta}{\Delta\lambda}\frac{\lambda}{c}=\frac{\lambda}{c}\frac{1}{d\cos\theta}=\frac{\lambda}{c}\frac{1}{d\sqrt{1-\sin^2\theta}}=\frac{\lambda}{c}\frac{1}{\sqrt{d-\lambda^2/4}}. \quad (2)$$

Where c is light speed. The time delay caused by angular dispersion is expressed:

$$t_D=\xi\frac{D}{2}=\frac{D}{2}\frac{\lambda}{c}\frac{1}{\sqrt{d-\lambda^2/4}}. \quad (3)$$

Where D=60mm is diameter of the grating.

For the sake of balance between smoothing speed and irradiation uniformity, we define color cycle N_c=1, therefore we can induce d=1.37μm though the equation:

$$N_c=\frac{t_D}{T_{FWHM}}.$$

The electric field after the grating is written as

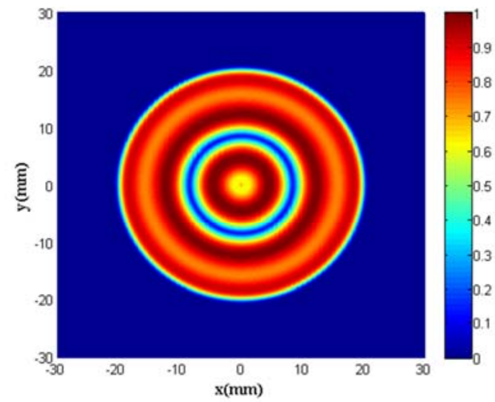
$$E(t)=\sum_{k=0}^{n}E(x,y)\alpha_k \exp\left[-\frac{(i+Ci)}{2\tau^2}(t-krT_{FWHM}+\xi r-\frac{Z}{c})^2\right]e^{-i\omega_0(t-krT_{FWHM})} \quad (5)$$

4. Intensity distribution contrast

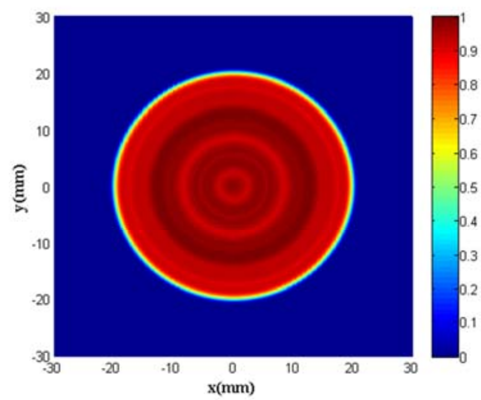
In this section we use a two-dimensional linear grating with the same dispersion parameter in x and y direction as the contrast object. For simplicity, we set α_k=1, k=0.7

$$E(x, y) = \exp\left[-\left(\frac{x^2 + y^2}{r_0^2}\right)^{20}\right] \tag{6}$$

Where r0=20 mm. To evaluate spectral smoothing effect, we simulate the electric field at the near-field.

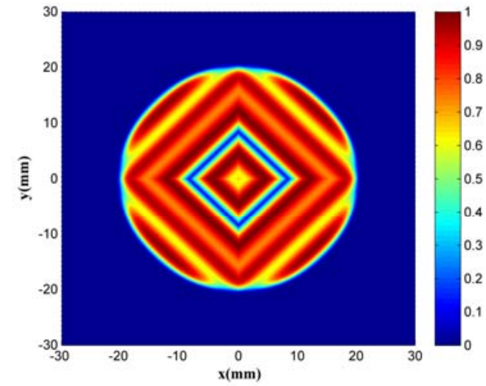


(a)

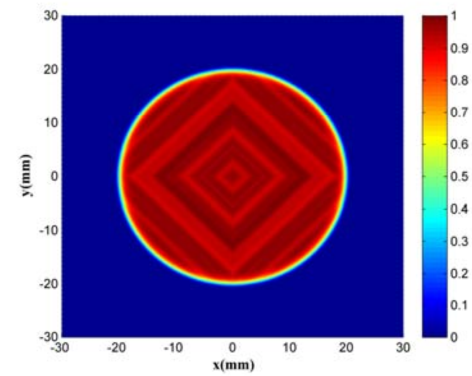


(b)

Fig. 3. Intensity used circular grating in near-field (a) temporal result (b) integral result (integral time is 3 ns)



(a)



(b)

Fig. 4 Intensity linear grating in near-field (a) temporal result (b) integral result (integral time is 3 ns)

For spherical circular grating as shown in Fig. 3, the root mean squares (RMS) of temporal and integral results are 21.1% and 11.6%, respectively. Whereas the counter-part values of linear grating are 19.6 % and 11.9 %, respectively, as shown in Fig. 4. Although gratings are different, the electric fields at near-field are the same except slightly difference between them.

Though they can be viewed as equal in near-field, our main concern is intensity distribution of far-field. For focal-plane, the light intensity distribution is Fourier Transformation of Eq. (5). The formula is below:

$$I = \iint E(X, Y, t) \exp \frac{\pi}{\lambda f}(Xx + Yy) dXdY \qquad (7)$$

When not combined with spatial smoothing approach, Figure 7 demonstrates the focal distribution.

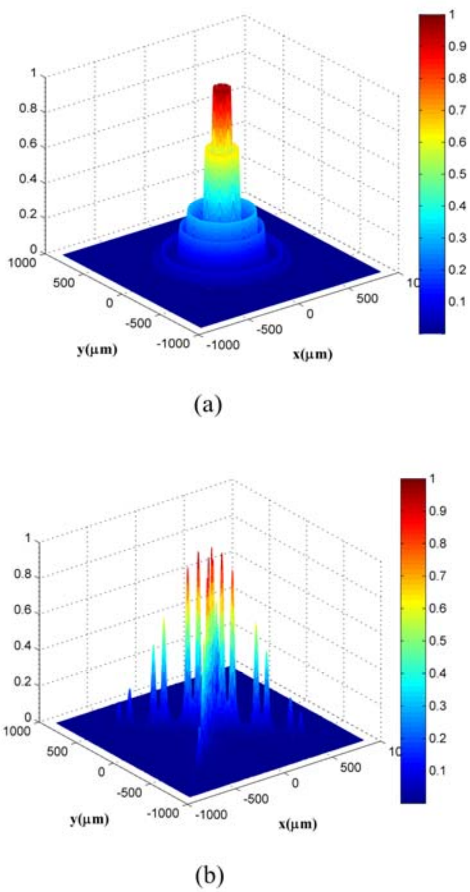


Fig. 5 integral focal plane intensity (a) spherical circular grating (b) linear gratings.

Compared between Fig. 5 (a) and Fig. 5 (b), it can be seen that the intensity distribution has a more uniform profile using spherical circular grating than using linear grating does. For linear grating, color cycle N_c equals 1 only in the two dispersion directions and less than 1 in other directions. For circular grating N_c equals 1 in all directions, so light beam have more spatial skew area in the latter situation than in former, which leads to a smoother profile [10].

In order to combine SSD and spatial smoothing, we designed a continuous phase plate (CPP) [11]. For quantitative discussion we calculated irradiation non-uniformity in 90% of total energy area on focal plane. When linear grating is inserted in the ICF system, the RMS=10.98 %, at the same time, RMS=9.6 %when inserting spherical circular grating. There is about 10 % improvement. Fig. 6 plots the focal beam pattern.

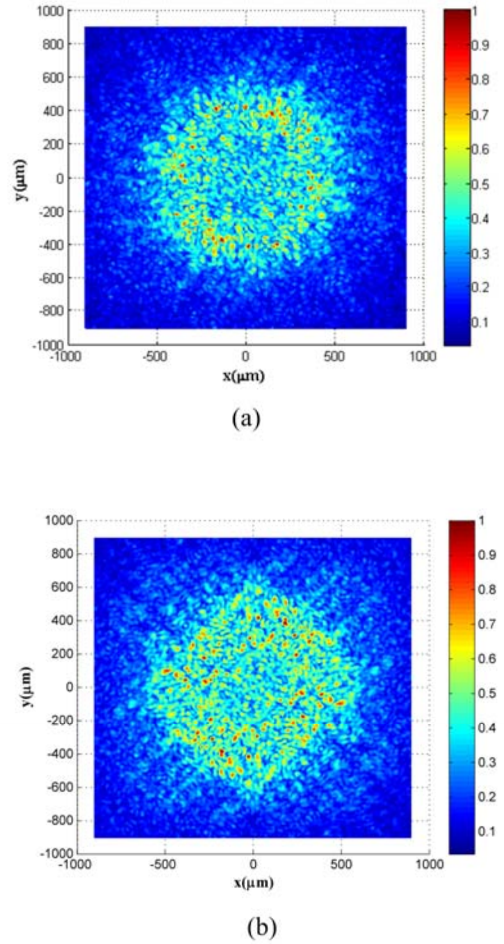


Fig. 6 focal beam pattern (a) spherical circular grating + CPP, (b) linear grating + CPP

We substitute one grating for two gratings in SSD technology and achieve the same result as linear gratings do, providing the elimination of modulator because of chirp effect. It successfully reduces complexity of system such as 3D-SSD system and makes adjustment easier.

5. Conclusion

We have discussed in detail the dispersion characteristics of circular grating theoretically, and then compared it's smoothing effect with that of linear gratings on near-field and focal plane. Our calculation shows that the smoothing effect using circular grating can raise irradiation uniformity by 10 % with same performance in near field. Hopefully, it is an option of advance of SSD technology.

Acknowledgments

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