The influence of smoothing by spectral dispersion on the beam characteristics in the near field*

Fan Xin-Min(樊心民), Lü Zhi-Wei(吕志伟)†, Lin Dian-Yang(林殿阳), and Wang Yu-Lei(王雨雷)

National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150080, *China*

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The influences of SSD on the beam characteristics in the near field are investigated. Results show that if the SSD parameters are increased, the laser intensity modulation increases while fluence modulation decreases, which is attributed to the temporal and spatial variation of the SSD pulse phase. The variations of intensity and fluence modulations with the SSD parameters are given. The simulation results are presented along with a method for choosing appropriate SSD parameters according to the variations and the requirements of applications.

Keywords: smoothing by spectral dispersion, intensity modulation degree, fluence modulation degree

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1. Introduction

Smoothing by spectral dispersion (SSD) is usually used for laser-irradiation uniformity in the far field for fusion lasers. To achieve optimal performance of the inertial confinement fusion (ICF) target, capsule irradiation by the driver laser beams must be sufficiently uniform,[1] so a number of beam-smoothing techniques have been pursued.[2–6] Among them, smoothing by spectral dispersion (SSD), a dynamic smoothing technique, has produced considerable improvement in laser-irradiation uniformity in the far field.[5–10] In light of the application prospects of SSD in thefar field, the influences of SSD on the near-field characteristics of the beam have also aroused great interest.[11–16]

In 1991, Skeldon *et al.* demonstrated experimentally that SSD could suppress the SRRS in a long air path, and they considered that one of the reasons for the suppression effect was that SSD smoothed the hot spots (to be more exact, the fluence[12]) across the beam in the near field.[11] In 1994, McKenty *et al.* proposed, via theoretical calculation, that SSD could raise the self-focusing threshold.[13] In 1997, Rothenberg *et al.* proved, through experiment, that SSD lowers the contrast of diffraction rings in free space.[14] In 2006, Jiang *et al.* indicated, by simulation, that SSD could improve the laser uniformity in the near field via controlling SSD parameters.[15] In 2009, Cheng *et al.* showed the physical mechanism and the conditions of the SSD suppression of small-scale self-focusing.[16]

In fact, both raising the thresholds of SRRS and self-focusing and lowering the contrast of diffraction rings, all of which helps elevate the load capacity of high-energy and high-power laser systems, are attributed to the influences of SSD on the laser intensity and fluence in the near field. So it is important to clarify the variations of the laser intensity and fluence with the SSD parameters and the relevant physical mechanism. This is our focus and contribution in this paper. The detailed work is given by simulation and analysis in the rest of this paper as follows. In Sections 2, 3, and 4, we give the related theories, the simulation results and analyses, and the concluding remarks, respectively.

2. Related theories

According to Ref. [5], SSD is obtained by an electro–optic modulator broadening the bandwidth of the initial monochromatic laser and two pieces of grating introducing spectral angular dispersion across the transverse direction of the beam. The initial monochromatic plane wave becomes broadband light with the phase varying in both time and space. In addition, the phase of the laser will be modulated and distorted as it passes through the optical components in the laser system, the distorted phase is named as an additional phase with a random distribution and can be expressed as[17,18]

$$\varphi_0(x) = \varphi_{0\mathrm{L}}(x) + \varphi_{0\mathrm{H}}(x), \tag{1}$$

where

$$\varphi_{0\mathrm{L}}(x) = A \cdot \mathrm{Random}(-1,1) \otimes \exp\left[-\left(\frac{x}{S_x}\right)^2\right], \tag{2}$$

$$\varphi_{0\mathrm{H}}(x) = \sigma \cdot \mathrm{Random}(-1,1). \tag{3}$$

Here, $\varphi_{0\mathrm{L}}(x)$ and $\varphi_{0\mathrm{H}}(x)$ represent the low and the high frequency additional phase, respectively. The low frequency $\varphi_{0\mathrm{L}}(x)$ follows a random Gaussian distribution, generated by convolving a Gaussian function with a uniformly distributed

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†Corresponding author. E-mail: zw_lu@sohu.com

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random number sequence, where A is the amplitude coefficient and S_x is the factor determining the size of the phase distortion along the x axis. The high frequency $\varphi_{0\mathrm{H}}(x)$ is a uniformly random distribution, where σ is the disturbing amplitude.

In the simulation discussed below, we use a one-dimensional model along the x axis to describe the transverse variations of physical quantities considering the spatial symmetry of the beam. According to Eq. (5) of Ref. [5], the electric field of the SSD pulse under the slowly varying amplitude approximation can be written as

$$E_{\mathrm{L}}(x,t) = E_{\mathrm{L0}}(x,t)\exp\left\{\mathrm{i}\delta\sin\left[2\pi\left(\nu_{\mathrm{m}}t+\beta\frac{\nu_{\mathrm{m}}}{\nu_0}x\right)\right] + \mathrm{i}\varphi_0(x)\right\}, \tag{4}$$

where $E_{\mathrm{L0}}(x,t)$ is the real amplitude of the electric field, $\varphi_0(x)$ is the additional phase across the beam, δ and ν_{m} are the modulation amplitude and frequency respectively, $\beta = \Delta\theta/\Delta\lambda$ is the grating dispersion coefficient, ν_0 is the laser central frequency. Obviously, the characteristics of the phase of the SSD beam are determined mainly by the three parameters of the modulation amplitude δ, modulation frequency ν_{m}, and grating dispersion coefficient β.

When implementing SSD on a laser system, the laser peak intensity should be limited while the laser fluence uniformity should be improved;[5] otherwise, many unwanted nonlinear optical effects such as self-focusing and stimulated light scattering will occur, which lead to laser energy losses and even optical element damage.[19–29] Therefore, it is necessary to study how the SSD affects the laser intensity and fluence in the near field for the application of SSD and the design of laser systems. Modulation degree is one of key parameters describing the characteristics of a laser beam in the near field. For a flat-topped pulse, the intensity modulation degree M_{I} and the fluence modulation degree M_{F} can be expressed as[30]

$$M_{\mathrm{I}} = \frac{I_{\max}}{I_{\mathrm{avg}}}, \tag{5}$$

$$M_{\mathrm{F}} = \frac{F_{\max}}{F_{\mathrm{avg}}}, \tag{6}$$

where $I_{\max}$, I_{avg}, $F_{\max}$, and F_{avg} represent the peak intensity, the average intensity, the peak fluence, and the average fluence, respectively.

3. Simulation results and analyses

In free space, the laser beam is governed by the Helmhotz equation during propagation:[24]

$$\nabla^2 E(x,t) - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}E(x,t) = 0, \tag{7}$$

where c refers to the velocity of light in vacuum. Substituting Eq. (4) into Eq. (7), we can get the variations of the intensity and the fluence modulation degrees of the SSD beam. In the simulation discussed below, for the initial laser, both the temporal and the spatial distributions are 18-order super-Gaussian, the central wave-length, the intensity, the full-width, and the diameter are 1053 nm, 2 GW/cm^2, 3 ns, and 10 cm, respectively; the parameters of the initial additional phase $\varphi_0(x)$ are $A = 1$, $S_x = 5$ cm, $\sigma = 0.2$. For simplicity, the size of the divergence angle of the beam is neglected.

The simulation results show that both the intensity and the fluence modulation degrees of the SSD beam change during transmission under different modulation parameters, however, and their variation rules are different, as shown in Fig. 1. With the increase of the transmission distance z, the intensity modulation degree M_{I} always changes and increases overall with a larger change range as the SSD parameters increase, as shown in Fig. 1(a). With the increase of the transmission distance z, the fluence modulation degree M_{F} also always changes; however, its change range becomes small and M_{F} even decreases overall as the SSD parameters increase, as shown in Fig. 1(b). From the different variations of the intensity and the fluence modulation degree represented in Figs. 1(a) and 1(b), we can deduce that the distribution of the intensity of the SSD beam will vary not only in space but also in time as the transmission distance z increases.

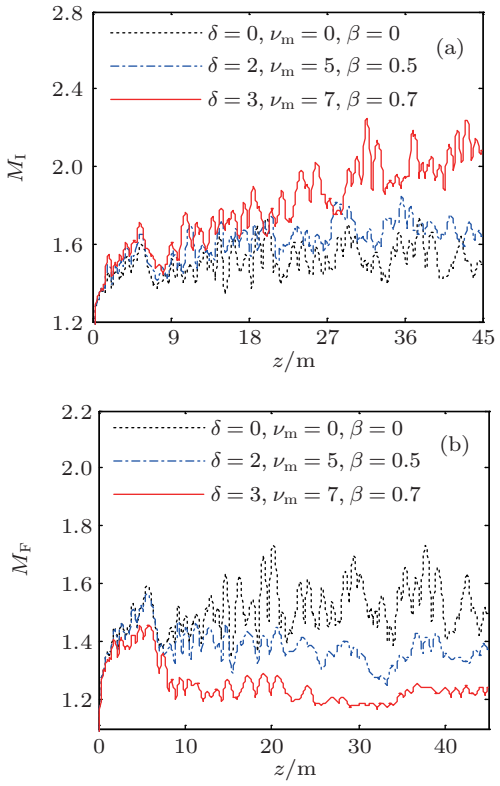


Fig. 1. (color online) The variations of (a) the intensity modulation degree M_{I} and (b) the fluence modulation degree M_{F} with the transmission distance z ($0 \sim 45$ m) under different modulation parameters.

From Fig. 1, it can be seen that SSD can significantly change the beam characteristics in teh near field: when the modulation parameters of modulation amplitude, modulation

frequency, and grating dispersion coefficient increase, the intensity modulation degree increases while the fluence modulation degree decreases; that is to say, SSD will damage the intensity distribution and smooth the fluence distribution. Therefore, it is vital to find out how the intensity and the fluence modulation degrees change with the SSD parameters to avoid the loss of laser energy and the damage of optical components before using SSD to smooth a focal spot in teh far field or suppress nonlinear effects in the near field.

We define $M_{\rm Ia}$ and $M_{\rm Fa}$ as the averages of the intensity modulation degree $M_{\rm I}$ and the fluence modulation degree $M_{\rm F}$ over the whole transmission distance. Figure 2 shows how $M_{\rm Ia}$ and $M_{\rm Fa}$ vary with the SSD parameters of the modulation amplitude β, the modulation frequency $\nu_{\rm m}$, and the grating dispersion coefficient β, where the transmission distance equals 45 m, the solid and the dotted lines represent the variations of $M_{\rm Ia}$ and $M_{\rm Fa}$, respectively. In practical application, the grating dispersion coefficient must satisfy $\beta \leq 2$ mrad/nm to achieve high harmonic conversion efficiency,[5] and the modulation amplitude β limited by modulator voltage is relatively small, and consequently we take $0 \leq \beta \leq 5$, $0 \leq \nu_{\rm m} \leq 15$ GHz, and $0 \leq \beta \leq 2$ mrad/nm in the simulation.

From Fig. 2, it can be seen: 1) With the increase of the three modulation parameters, the average fluence modulation degrees $M_{\rm Fa}$ all decrease and their ranges are nearly identical, but their variations are slightly different: with the increase of the modulation amplitude β, the laser average fluence modulation degree $M_{\rm Fa}$ decreases first with tiny fluctuation, followed by a slow climb. However, the laser average fluence modulation degrees $M_{\rm Fa}$ decrease monotonically with the increase of the modulation frequency $\nu_{\rm m}$ and the grating dispersion coefficient β, and their variation rules are similar. 2) With the increase of the three modulation parameters, the average intensity modulation degrees $M_{\rm Ia}$ first increase, and then decrease. The variation rules of $M_{\rm Ia}$ with the modulation frequency $\nu_{\rm m}$ and the grating dispersion coefficient β are similar. 3) With the increase of the three modulation parameters, the variation ranges of $M_{\rm Ia}$ are larger than those of $M_{\rm Fa}$, which proves that SSD has a larger impact on the intensity than on the fluence.

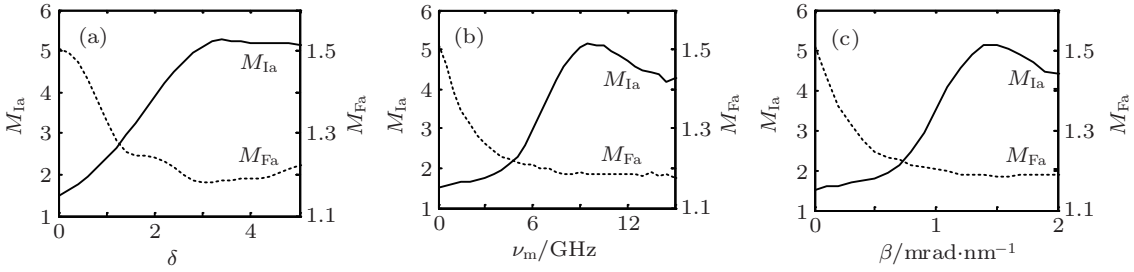


Fig. 2. The variations of the average intensity modulation degree $M_{\rm Ia}$ and the average fluence modulation degree $M_{\rm Fa}$ with (a) the modulation amplitude δ ($\nu_{\rm m} = 10$ GHz, $\beta = 1.5$ mrad/nm), (b) the modulation frequency $\nu_{\rm m}$ ($\delta = 3$, $\beta = 1.5$ mrad/nm), and (c) the grating dispersion coefficient β ($\delta = 3$, $\nu_{\rm m} = 10$ GHz) over the transmission distance of 45 m.

In general, the near-field transmission characteristics of the laser beam in free space are determined by the distribution of the initial phase. For the SSD beam, changing the parameters of modulation amplitude, modulation frequency or grating dispersion coefficient is just changing the distribution of the initial phase. As shown in Eq. (4), the distribution of initial phase of the SSD laser pulse is

$$\varphi(x,t) = \delta \sin\left[2\pi\left(\nu_{\rm m}t + \beta\frac{\nu_{\rm m}}{\nu_0}x\right)\right] + \varphi_0(x). \qquad (8)$$

Obviously, $\varphi(x,t)$ varies continuously with time and space, as shown in Fig. 3(a), where the modulation parameters are $\beta = 3$, $\nu_{\rm m} = 5$ GHz, and $\beta = 1.5$ mrad/nm. So the intensity distribution across the beam will be modulated by a diffraction effect during propagation, as shown in Fig. 3(b). The dotted and the solid lines represent the transverse distribution of the laser intensity at the central instant of pulse at the initial position ($z = 0$) and 10 m far away ($z = 10$ m) respectively. However, the variations of the phase at each instant are similar throughout the entire SSD pulse, merely their positions move continuously along x axis in the same direction as time goes on, as do those of the laser peak intensities of each instant. Therefore the laser fluence modulation degree of the SSD beam will decrease.

The research results above show that we can control the laser intensity and fluence modulation in the near field by SSD to meet the requirements of different applications. For example, to protect the optical components from damage, the average intensity modulation degree must satisfy $M_{\rm Ia} \leq 1.7$ over the transmission distance of 45 m, and we can choose appropriate SSD parameters according to Fig. 4(a). The curved surface represents the satisfactory maximum grating dispersion coefficient $\beta_{\rm max}$ when $0 \leq \beta \leq 5$ and $0 \leq \nu_{\rm m} \leq 15$ GHz, the average intensity modulation degree $M_{\rm Ia}$ will not be larger than 1.7 as long as the chosen grating dispersion coefficient β satisfies $\beta \leq \beta_{\rm max}$, the number of the satisfactory grating dispersion coefficient β declines with the increase of the modulation amplitude β and/or the modulation frequency $\nu_{\rm m}$. Also, if we expect that the average fluence modulation degree satisfies $M_{\rm Fa} \leq 1.4$ over the transmission distance of 45 m,

we can choose the appropriate SSD parameters according to

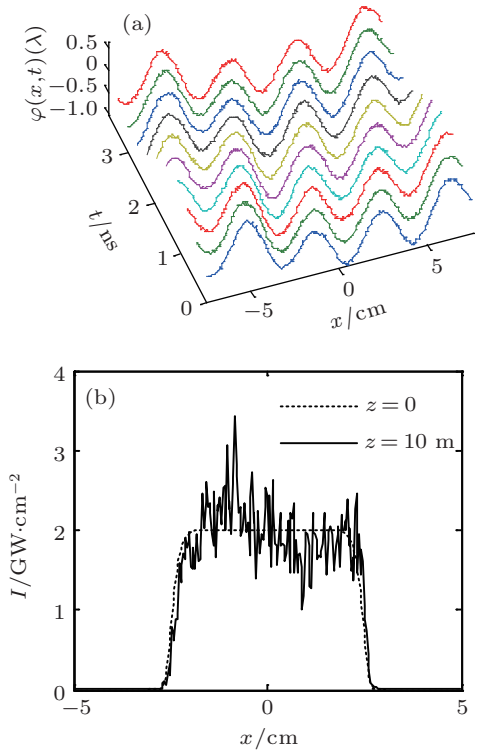


Fig. 3. (color online) The distributions of (a) the initial phase $\varphi(x,t)$ and (b) the laser intensity at the central instant of pulse at the positions of $z=0$ (dotted line) and $z=10$ m (solid line) when $\beta=3$, $\nu_{\rm m}=5$ GHz, and $\beta=1.5$ mrad/nm.

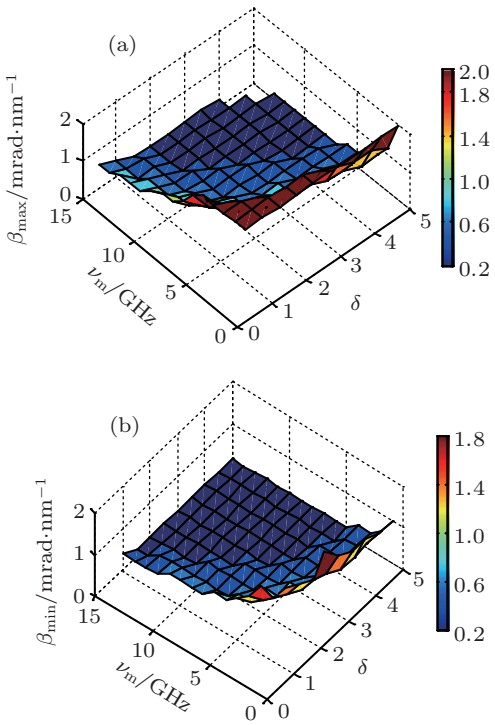


Fig. 4. (color online) The variations of (a) the satisfactory maximum grating dispersion coefficient $\beta_{\max}$ (when $M_{\rm Ia}\leq 1.7$) and (b) the satisfactory minimum grating dispersion coefficient $\beta_{\min}$ (when $M_{\rm Fa}\leq 1.4$) with the modulation amplitude δ and the modulation frequency $\nu_{\rm m}$ when the transmission distance equals 45 m.

Fig. 4(b). The curved surface represents the satisfactory minimum grating dispersion coefficient $\beta_{\min}$ when $0\leq\beta\leq 5$ and $0\leq\nu_{\rm m}\leq 15$ GHz, the average fluence modulation degree $M_{\rm Fa}$ will not be larger than 1.4 as long as the chosen grating dispersion coefficient β satisfies $\beta\geq\beta_{\min}$, the number of the satisfactory grating dispersion coefficient β increases with the increase of modulation amplitude δ or/and modulation frequency $\nu_{\rm m}$. The SSD pulse over the transmission distance of 45 m will satisfy both $M_{\rm Ia}\leq 1.7$ and $M_{\rm Fa}\leq 1.4$ if the chosen dispersion coefficient β satisfies $\beta_{\min}\leq\beta\leq\beta_{\max}$ when $0\leq\delta\leq 5$ and $0\leq\nu_{\rm m}\leq 15$ GHz.

4. Conclusions

In this paper, the influences of SSD on the beam characteristics in the near field are investigated. The results show that SSD will damage the intensity distribution while smoothing the fluence distribution when the modulation parameters increase, all of which is caused by the temporal and spatial variation of the phase of SSD beam. So it is vital to choose appropriate SSD parameters to avoid the loss of laser energy and the damage to optical components. We give a method of choosing appropriate SSD parameters according to different requirements. This study will help in expanding SSD applications.

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