Improving irradiation uniformity by lens array with beam spectral dispersion

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A scheme of combining smoothing by spectral dispersion (SSD) technology with lens array (LA) is introduced in laser produced shock wave experiments. The feasibility of the scheme is analyzed by numerical simulation. It is shown that the beam uniformity in near field could be improved by the phase modulation and spectral dispersion, and a smoothed pattern with flat-top and sharp-edge profile could be obtained in the focal plane. The irradiation nonuniformity of the focal pattern depends on the design of both SSD and LA but less on the incident beam in comparison with other smoothing methods. Experiments are conducted by adopting the schemes of LA and SSD, distributed phase plate (DPP) and SSD. The results are beneficial for better smoothing in laser-plasma interaction experiments in the future.

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Uniform irradiation on target plane is essential in laser produced shock wave experiments, and a focal pattern with sharp-edge and flat-top profile is required especially in the research of state equations. Several beam-smoothing technologies have been proposed to improve laser irradiation uniformity on the target plane[1−7]. These technologies can be summarized into two categories: 1) the spatial smoothing approach of breaking the beam up spatially into fine-scale structure, including random phase plate (RPP)[1], distributed phase plate (DPP)[2,8], and lens array (LA)[3], etc.; 2) the temporal smoothing approach of causing the structure to change rapidly with time and giving the beam with time-averaged smoothness, including induced spatial incoherence (ISI)[4] and smoothing by spectral dispersion (SSD)[5], etc..

Usually two or more techniques are used in one scheme to get better effect of beam smoothing. The technology of LA has been successfully implemented on Shenguang (SG) I, II facilities for many years[3], in which quasi-near-field diffraction patterns are obtained and overlap with each other to realize smoothing on the focal plane. But the beam spatial profiles with LA irradiating includes highly modulated speckles caused by interference among different LA elements, which are expected to be smoothed by SSD. In this paper, a scheme of combining LA with SSD is introduced to improve the irradiation uniformity.

LA beam smoothing, as shown in Fig. 1, is composed of a principal focusing lens A with focal length of f_a, and a lens array B consisting of multiple similar smaller hexagonal or square lenses placed ahead of A[3]. The lens array splits the incident beam into many partial beamlets, and each of them focuses onto a focal surface E, and then diverges and illuminates in the common focal plane C of principal lens A. The beam in focal plane will be smoothed because of each beamlet overlapping in a same position of the plane C, and an approximate flat-top intensity can be obtained. In fact, the target surface C' is moved a little backward from plane C to get a more smoothing illumination effect. If a LA is composed of $N \times N$ square lenses, with the elementary aperture d and focal length f_c, then its transmittance is

$$T(x,y) = \sum_{m=-M/2}^{M/2} \sum_{n=-N/2}^{N/2} P(x-md, y-nd) \exp\{-j\frac{k}{2f_c}[(x-md)^2+(y-nd)^2]\}. \quad (1)$$

And P is the pupil function defined by

$$P(x,y) = \begin{cases} 1, & \text{inside the sublens aperture} \\ 0, & \text{others} \end{cases}. \quad (2)$$

The size of the focal spot δ may be written as

$$\delta = f_a d / f_c. \quad (3)$$

And the spatial frequency induced by different element lens interference is

$$\Gamma = \lambda F K^{-1}, \quad (4)$$

where F is the F-number of the principal focal lens, and K is the number of element lenses of LA.

Figure 2 is a schematic of the SSD technique. Broadband light produced by electro-optic (EO) phase-modulation (PM) is spectrally dispersed by a grating[5]. The electric field after that is given by

$$\begin{aligned} & E_D(x,y,t) \\ & = E_0(x,y,t)\exp\{i2\pi\nu t + i\delta\sin[2\pi(\nu_m t + \frac{\Delta\theta}{\Delta\lambda}\frac{\nu_m}{\nu}Y)]\} \\ & = E_0(x,y,t)\sum_n J_n(\delta)\mathrm{e}^{i2\pi(\nu+n\nu_m)t}\mathrm{e}^{in\alpha y}, \end{aligned} \quad (5)$$

where E_0 and ν are the amplitude and frequency of incident beam, ν_m and δ are the modulation frequency and

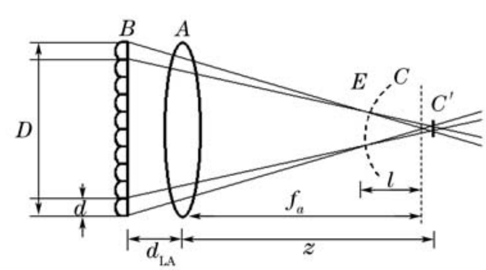

Fig. 1. Scheme of LA beam smoothing.

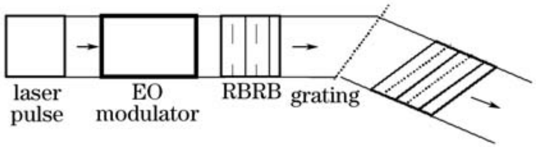

Fig. 2. Scheme of SSD beam smoothing.

the modulation depth, respectively, $\frac{\Delta\theta}{\Delta\lambda}$ is the grating dispersion, and denoting $\alpha = 2\pi\frac{\Delta\theta}{\Delta\lambda}\frac{\nu_m}{\nu}$. The beam contains frequency side bands in increments of ν_m because of the effect of SSD, which extend out to approximately $\pm\delta\nu_m$, and the frequency spreading is well approximated by $\Delta\nu = 2\cdot\delta\cdot\nu_m$.

The instantaneous frequency of output laser can be expressed as

$$\nu_t(t) = \nu + \delta\nu_m \cos(2\pi\nu_m t + \alpha Y). \tag{6}$$

The instantaneous frequency varies across the beam in the direction of dispersion (y-direction) with a period of $\frac{2\pi}{\alpha}$ for the time delay t_{D} introduced by grating, and the temporal modulation of beam is transformed into spatial modulation called as "color cycling", and the maximum of which is defined as

$$N_{\mathrm{c}} \equiv t_{\mathrm{D}}\nu_m = D\frac{\alpha}{2\pi} = D\frac{\Delta\theta}{\Delta\lambda}\frac{\lambda}{c}\nu_m. \tag{7}$$

Combining LA and SSD, the electric field of beam passing through a SSD system and LA may be written as

$$E(x,y,t) = E_D(x,y,t)T(x,y). \tag{8}$$

According to Collins equation[9], the electric field of light passing the principal focal lens is

$$E_t(x,y) = -\frac{j}{\lambda B}\iint E_D(x_0,y_0)T(x_0,y_0) \exp[jkL(x,y;x_0,y_0)]\mathrm{d}x_0\mathrm{d}y_0, \tag{9}$$

where L is eikonal of the LA system from LA to target plane,

$$L(x,y;x_0,y_0) = L_0 + \frac{1}{2B}\left[A(x_0^2+y_0^2) -2(xx_0+yy_0) + D(x^2+y^2)\right], \tag{10}$$

A, B, C, D can be described by transmittance matrix of focusing lens shown in Fig. 1:

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1-z/f_a & d_{\mathrm{LA}}(1-z/f_a)+z \\ -1/f_a & 1-d_{\mathrm{LA}}/f_a \end{pmatrix}, \tag{11}$$

z is the distance between focusing lens and target plane, d_{LA} is the distance between focusing lens and lens array.

When $z = f_a$ and $A = 0$, the electric field is on the focal plane,

$$\begin{aligned} E(x,y,t,f_a) &= \frac{\exp(ikL_0)}{i\lambda f_a}\exp[\frac{ik}{f_a}D(x^2+y^2)] \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} E(x_0,y_0,t,0)\exp\{-\frac{ik}{f_a}(xx_0+yy_0)\}\mathrm{d}x_0\mathrm{d}y_0 \\ &= \frac{\exp(ikL_0)}{i\lambda f_a}\exp[\frac{ik}{f_a}D(x^2+y^2)]\sum_n J_n(\delta)\mathrm{e}^{i2\pi(\nu+n\nu_m)t} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} E_0(x_0,y_0,t,0)T(x_0,y_0)\mathrm{e}^{in\alpha y_0} \exp\{-\frac{ik}{f_a}(xx_0+yy_0)\}\mathrm{d}x_0\mathrm{d}y_0. \end{aligned} \tag{12}$$

After the time of pulse length τ, the time-averaged beam intensity in the focal plane is

$$I = \frac{1}{\tau}\int_0^{\tau} \left|E(x,y,t,f_a)\right|^2 \mathrm{d}t. \tag{13}$$

To simplify the analysis, only one dimension (the direction of dispersion) is considered, Eq. (12) becomes

$$\begin{aligned} &E(y,f_a,t) \\ &= \frac{\exp(ikL_0)}{(i\lambda f_a)^{1/2}}\exp[\frac{ik}{f_a}D(y^2)]\sum_n J_n(\delta)\mathrm{e}^{i2\pi(\nu+n\nu_m)t} \int_{-\infty}^{+\infty} E_0(y_0,t,0)T(y_0)\mathrm{e}^{in\alpha y_0}\exp(-\frac{ik}{f_a}yy_0)\mathrm{d}y_0 \\ &= \frac{\exp(ikL_0)}{(i\lambda f_a)^{1/2}}\exp[\frac{ik}{f_a}D(y^2)]\sum_n J_n(\delta)\mathrm{e}^{i2\pi(\nu+n\nu_m)t} \int_{-\infty}^{+\infty} E_0(y_0,t,0)T(y_0)\mathrm{e}^{-i\frac{k}{f_a}y_0(y-\frac{n\alpha f_a}{k})}\mathrm{d}y_0 \\ &= \frac{\exp(ikL_0)}{(i\lambda f_a)^{1/2}}\exp[\frac{ik}{f_a}D(y^2)] \sum_n J_n(\delta)E'(y-\frac{n\alpha f_a}{k})\mathrm{e}^{i2\pi(\nu+n\nu_m)t}, \end{aligned} \tag{14}$$

where E' is the electric field of focal plane when only LA system is used, and the dispersion angle for the nth harmonic, θ_n, may be given by

$$\theta_n = -\frac{\Delta\theta}{\Delta\lambda}\frac{\lambda}{\nu}n\nu_m = n\theta_m \quad (\theta_m = -\frac{\Delta\theta}{\Delta\lambda}\frac{\lambda\nu_m}{\nu}). \tag{15}$$

And we can conclude the relationship of

$$\frac{n\alpha f_a}{k} = f_a\theta_n = nf_a\theta_m. \tag{16}$$

Equation (14) becomes

$$E(y,f_a,t) = \frac{\exp(ikL_0)}{(i\lambda f_a)^{1/2}}\exp[\frac{ik}{f_a}D(y^2)] \sum_n J_n(\delta)E'(y-nf_a\theta_m)\mathrm{e}^{i2\pi(\nu+n\nu_m)t}. \tag{17}$$

The focal pattern will shift $nf_a\theta_m$ for each frequency $\nu+n\nu_m$ with the amplitude of $J_n(\delta)E'(y-nf_a\theta_m)$ when

SSD is added. And the maximum shift of beam in the focal plane is

$$\Delta l = f_a \cdot \delta\theta/2, \tag{18}$$

where $\delta\theta$ is the maximum beam dispersion angle induced by grating and phase modulator. And the intensity modulation of focal pattern will be decreased with the spatial frequency lower than $2\Delta l$ smoothed for the application of SSD.

To get a more smoothing effect in a scheme of LA, the target plane is often little away from the focal plane of principal focal lens at a distance of Δ. Some parameters will be different, such as $z = f_a + \Delta$, $A \neq 0$ and $B \approx f_a$, and the electric field of output may be written as

$$\begin{aligned} &E(y,z,t) \\ &= \frac{\exp(ikL_0)}{(i\lambda B)^{1/2}} \sum_n J_n(\delta) \mathrm{e}^{i2\pi(\nu+n\nu_m)t} \mathrm{e}^{iDn\alpha y} \mathrm{e}^{ik(\frac{D}{2B}\frac{n^2\alpha^2B^2}{k^2})} \\ &\int_{-\infty}^{+\infty} E_0(y_0,t,0)T(y_0) \mathrm{e}^{i\frac{k}{2B}[Ay_0^2 - 2y_0(y-\frac{n\alpha B}{k}) + D(y-\frac{n\alpha B}{k})^2]} \mathrm{d}y_0 \\ &= \frac{\exp(ikL_0)}{(i\lambda B)^{1/2}} \sum_n J_n(\delta) \mathrm{e}^{iDn\alpha y} \mathrm{e}^{ik(\frac{D}{2B}\frac{n^2\alpha^2B^2}{k^2})} \\ &\quad E''(y - \frac{n\alpha B}{k}) \mathrm{e}^{i2\pi(\nu+n\nu_m)t} \\ &\approx \frac{\exp(ikL_0)}{(i\lambda B)^{1/2}} \sum_n J_n(\delta) E''(y - \frac{n\alpha B}{k}) \mathrm{e}^{i2\pi(\nu+n\nu_m)t}, \end{aligned} \tag{19}$$

where E'' is the electric field of LA system target plane which is away from the focal plane. And because $\Delta \ll f_a$, $D\alpha y \approx 10^{-3}$ rad, $\frac{D}{2B}\frac{n^2\alpha^2B^2}{k^2} \approx 10^{-6}\,\mathrm{mm} \ll L_0 \approx d_{\mathrm{LA}} + f_a$, Eq. (19) becomes

$$\begin{aligned} &E(y, f_a+\Delta, t) \\ &\approx \frac{\exp(ikL_0)}{(i\lambda f_a)^{1/2}} \sum_n J_n(\delta) E''(y - \frac{n\alpha f_a}{k}) \mathrm{e}^{i2\pi(\nu+n\nu_m)t}, \end{aligned} \tag{20}$$

which is similar to Eq. (17). And the focal pattern is also smoothed by SSD though the basic profile is much flatter.

Based on the above analysis, the intensity distributions on target plane are simulated and only one dimension is considered. The incidence is at the wavelength λ of 1.053 μm and pulse width of 1 ns. And the designed size of focal pattern, the maximum beam aperture D_0 incident to grating, and the maximum beam aperture D incident to LA are 0.6, 35, and 350 mm. The grating dispersion $\frac{\Delta\theta}{\Delta\lambda}$ is 2.97 mrad/nm, and the effect of transversal thermal conduction[10] is considered.

In the design of LA, the F-number ($F = f_a/D$) of principal focusing lens is very important and a more smoothing and flat-top focal pattern can be obtained if a small F-number focal lens is considered. But it is better for SSD to adopt a big F-number according to Eq. (18). Some simulations are carried for different F-numbers, as shown in Fig. 3. The results show that the application of SSD can improve the uniformity of focal pattern smoothing by LA. However, uniformity is limited by hard-edge diffraction and interference of LA in quasi-near-field, which leads to difference from other spatial smoothing methods when combining with SSD.

But the effect of hard-edge diffraction can be decreased by apodized LA designing. Figure 4 shows the results of soft-edge element lens with application of SSD in different F-numbers, and the nonuniformity of SSD and LA with small F-number ($F = 2.14$) can down to 1.8%. But with big F-number ($F = 4.5$), there are still some modulations induced by interference in the pattern. Two methods can decrease the effect of interference by reducing the incident coherence: increasing δ, or decreasing ν_m and keeping bandwidth $\Delta\nu$ and dispersion angle $\delta\theta$ constant. But the beam bandwidth $\Delta\nu$ and dispersion $\delta\theta$ will increase too with the increase of δ, which may lead to the distortion of focal pattern profile that is decided

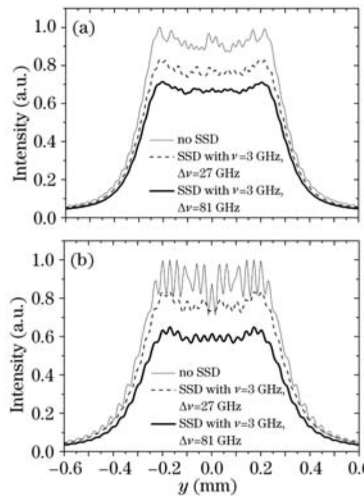

Fig. 3. One-dimensional (1D) intensity distributions of hard-edge LA and SSD. (a) $F = 2.14$, 11 element lenses, nonuniformity decreases from 5.4% to 2.2%; (b) $F = 4.5$, 7 element lenses, nonuniformity decreases from 16% to 4.1%.

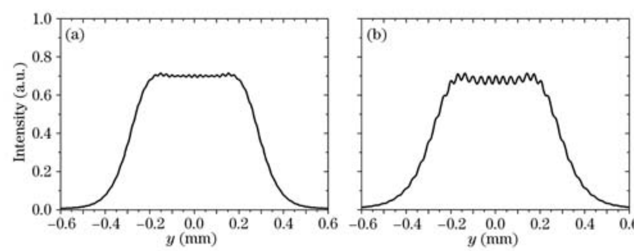

Fig. 4. 1D intensity distributions of soft-edge LA and SSD. (a) $F = 2.14$, 11 element lenses, and nonuniformity is about 1.8%; (b) $F = 4.5$, 7 element lenses, and nonuniformity is about 3.3%. SSD with $\nu = 3$ GHz, $\Delta\nu = 81$ GHz.

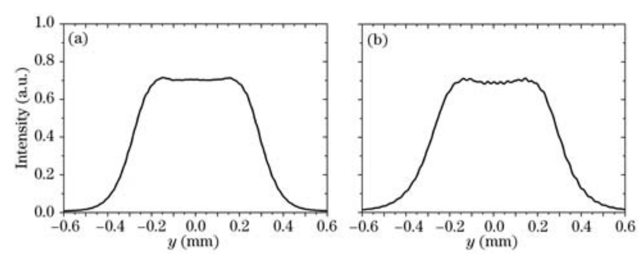

Fig. 5. 1D intensity distributions of soft-edge LA and SSD with decreased ν_m. (a) $F = 2.14$, the top is flat and there is no typical modulation; (b) $F = 4.5$, nonuniformity is about 1.1%. SSD with $\nu = 0.43$ GHz, $\Delta\nu = 81$ GHz.

by LA, as can be seen from Eq. (20). But $\Delta\nu$ and $\delta\theta$ are kept constant when decreasing ν_m, and the number of color cycle N_c is decreased too so that the incident frequency on element lens is different from each other, which can remove interference at most. Some results are shown in Fig. 5.

The incident wavefront is also important for any smoothing method because variations of wavefront such as amplitude modulation (AM) or PM may reduce irradiation uniformity on target plane. And usually the incidence deviates from the designing. However, the requirements of incidence on LA are weaker than other spatial smoothing approaches[3], so is in the using of SSD and LA. Figure 6 shows the results of comparing method of SSD+LA with SSD+DPP when there is distortion in incidence, and there are higher modulations in pattern of DPP than of LA.

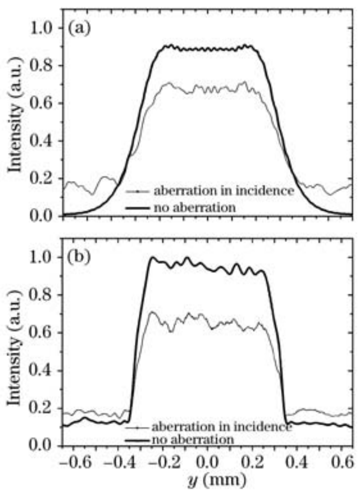

Fig. 6. 1D intensity distributions for different spatial smoothing methods. (a) SSD+LA ($F = 2.14$); (b) SSD+DPP. $\nu = 3$ GHz, $\Delta\nu = 81$ GHz.

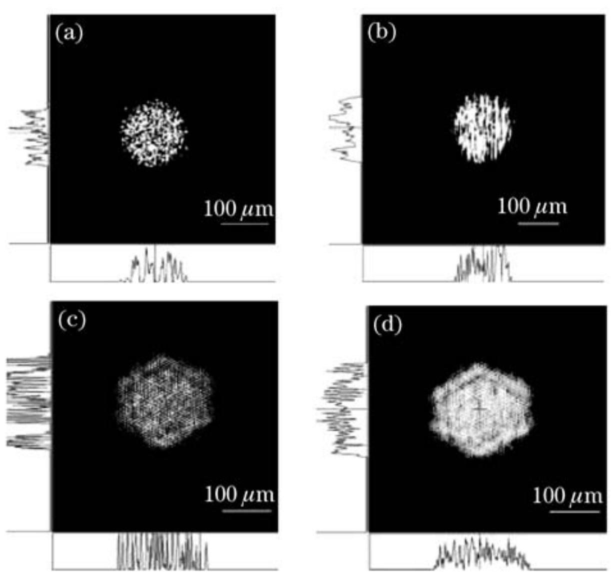

Fig. 7. Measured IR images of 2-ns laser pulse. (a) DPP without PM; (b) DPP with 1D SSD (in y-direction) at $\Delta\nu \approx 37$ GHz; (c) LA without PM; (d) LA with 1D SSD (in y-direction) at $\Delta\nu \approx 37$ GHz. The number of DPP elements is 512×512, and of LA is 7×6, and the F-number is 4.2.

Infrared (IR) images measured by charge-coupled device (CCD) of 2-ns laser pulse smoothed by different methods are presented in Fig. 7. The focal plane image was transferred on a CCD by a relay lens with $10\times$ magnification so that a more fine structure can be gotten and analyzed. The results illustrate that the effects of SSD with either DPP or LA are obvious and a more smoothing spatial intensity envelope (see the line distributions of pattern in Fig. 7) can be obtained in the direction of SSD. The high spatial frequency of nonuniformity in the pattern of LA results from hard-edge diffraction and interference of the elementary lens, and it can be more smooth with SSD. In experiments the incident beam was not a plane wave as required but with AM and PM, an approximate sharp-edge and flat-top envelope is remained by either DPP or LA. But some nonuniformity was still observed, especially of low spatial frequency. However, it is found that the technology of LA and SSD works well in Fig. 7(d) and the spatial profile is more flat.

In conclusion, a method of smoothing by LA and SSD is analyzed to improve the irradiation uniformity on the target plane. The basic profile of focal pattern depends on the design of LA, and the application of SSD can improve uniformity more. Some high modulations in the focal pattern caused by hard-edge diffraction can be improved by apodized LA designing, others still remain such as interference, but it can be removed by SSD with suitable parameters. The advantage of SSD and LA is that not only a smoothed focal pattern but also an approximated flat-top and sharp-edge profile can be got even if there is distortion in incidence, which is better than other spatial smoothing methods such as RPP and DPP.

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