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Beam smoothing by lens array with spectral dispersion

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Abstract

A scheme of combining technology of lens array (LA) and smoothing by spectral dispersion (SSD) is introduced to improve the irradiation uniformity in laser fusion based on the earlier works on LA. The feasibility of the scheme is also analyzed by numerical simulation. It shows that a focal pattern with flat-top and sharp-edge profile could be obtained, and the irradiation nonuniformity can fall down from 14% with only LA to 3% with both SSD and LA. And this smoothing scheme is depended less on the incidence comparing to other smoothing methods. The preliminary experiment has demonstrated its effectiveness.

Keywords: Irradiation non-uniformity; Smoothing by spectral dispersion; Lens array

1. Introduction

The smoothing of focal plane intensity distribution of high power lasers is very important to the goal of laser fusion research, and various beam-smoothing technologies have been proposed [1–7] to reduce the modulation of beam intensity. All of these technologies can be summarized into two categories: (1) the spatial smoothing approach of breaking the beam up spatially into fine-scale structure, including the technologies of random phase plate (RPP) [1], distributed phase plate (DPP) [2], and lens array (LA) [3], etc. and (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 we use two kinds approaches on one beam to get better effect of beam smoothing [4,8]. Although LA has successfully been implemented on SG-I, SG-II facility for many years [3], the beam spatial profiles with LA irradiating includes highly modulated speckles caused by interference among different LA elements. In this paper a scheme of combining LA with SSD is introduced and discussed to improve the irradiation uniformity.

2. Theory analysis

2.1. Lens array

This kind of beam smoothing, shown in Fig. 1, is composed of a principal focusing lens A with focal length of f_a, and a lens array B composed 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 the transmittance of lens array is:

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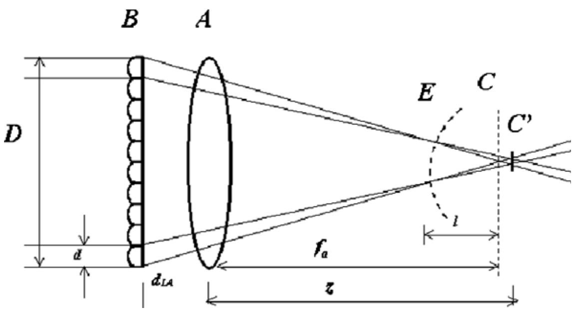

Fig. 1. The scheme of LA.

$$T(x,y)=\sum_{m=-M/2}^{M/2}\sum_{n=-N/2}^{N/2}\mathrm{rect}\left(\frac{x-x_{mn}}{d}\right)\mathrm{rect}\left(\frac{y-y_{mn}}{d}\right)\times\exp\left\{-\mathrm{j}\frac{k}{2fc}[(x-x_{mn})^2+(y-y_{mn})^2]\right\}. \quad (1)$$

According to Collins equation [9], the electric field of light in focal plane is:

$$E_t(x_t,y_t)=-\frac{\mathrm{j}}{\lambda B}\int\int E_0(x,y)T(x,y)\exp[\mathrm{j}kL(x,y;x_t,y_t)]\,\mathrm{d}x\,\mathrm{d}y, \quad (2)$$

where E_0 is the amplitude of incident beam, x and y are the coordinate of input, x_{mn} and y_{mn} is central coordinates of the mth line, nth row elementary lens, x_t and y_t are the coordinate of output, and the function L is eikonal of LA system from lens array to target plane:

$$L(x,y;x_t,y_t)=L_0+\frac{1}{2B}\left[A(x^2+y^2)-2(xx_t+yy_t)+D(x_t^2+y_t^2)\right], \quad (3)$$

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

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

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

The intensity of light in target is:

$$I_t(x_t,y_t)\propto E_t(x_t,y_t)E_t^*(x_t,y_t),$$

which is interference of multi-light beams with a envelop of Fresnel diffraction. The size of the focal spot δ may be written as:

$$\delta=f_{\mathrm{a}}d/f_{\mathrm{c}}. \quad (4)$$

2.2. Smoothing by spectral dispersion (SSD)

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

$$E_{\mathrm{D}}(x,y,t)=E_0(x,y,t)\exp\left\{\mathrm{i}2\pi vt+\mathrm{i}\delta\sin\left[2\pi\left(v_{\mathrm{m}}t+\frac{\Delta\theta}{\Delta\lambda}\frac{v_{\mathrm{m}}}{v}y\right)\right]\right\}, \quad (5)$$

where E_0 and v are the amplitude and frequency of incident beam, v_{m} and δ are the modulation frequency and the modulation depth, respectively, $\frac{\Delta\theta}{\Delta\lambda}$ is the grating dispersion, and denoting $\alpha=2\pi\frac{\Delta\theta}{\Delta\lambda}\frac{v_{\mathrm{m}}}{v}$.

The instantaneous frequency of output laser can be expressed as:

$$v_t(t)=v+\delta v_{\mathrm{m}}\cos(2\pi v_{\mathrm{m}}t+\alpha Y). \quad (6)$$

The instantaneous frequency varies across the beam in the direction (Y-axis) of dispersion with a period of $\frac{2\pi}{\alpha}$ for the time delay introduced by grating, and the temporal modulation of beam is transformed into spatial modulation called as “color cycling”.

2.3. The scheme of SSD + LA

As other spatial smoothing approaches, there are many highly spatial modulations for diffraction of elementary lens and interference between different beamlets in the focal pattern smoothed by LA. The small-scale spatial modulations can be smoothed by the effect of transversal thermal conduction [10]; others still exist, which limits the smoothing of the beam.

But that can be improved by a method of combining the technology of LA with SSD. Fig. 3 is a schematic of this method. In the laser system, beam with broad bandwidth and angular dispersion is generated by SSD at the front-end, and then amplified, extended, and focused through a LA onto a target at last. Since the electric field of incident beam to each elementary lens is not the same for frequency propagating at different angle in the direction of dispersion, the sub-patterns have some different spatially shift in the focal plane. With the beam spectral divergence $\Delta\theta$ and focal length f_{a}, we get the maximum shift Δl of sub-patterns in focal plane

$$\Delta l\approx\Delta\theta\cdot f_{\mathrm{a}}. \quad (7)$$

As the frequencies change throughout the length of the pulse, the rapidly fluctuating interference of the different sub-patterns causes the intensity distribution of focal pattern to get smooth on a time-averaged basis, with amplitude of spatial modulation decreasing which scale lower than Δl.

Based on Eqs. (1), (2) and (5), the electric field of smoothed beam in the focal plane is

$$E_t(x_t,y_t,t)=-\frac{\mathrm{j}}{\lambda B}\int\int E_{\mathrm{D}}(x,y,t)T(x,y)\exp[\mathrm{j}kL(x,y;x_t,y_t)]\,\mathrm{d}x\,\mathrm{d}y. \quad (8)$$

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

$$I=\frac{1}{\tau}\int_0^{\tau}|E_t(x_t,y_t,t)|^2\,\mathrm{d}t. \quad (9)$$

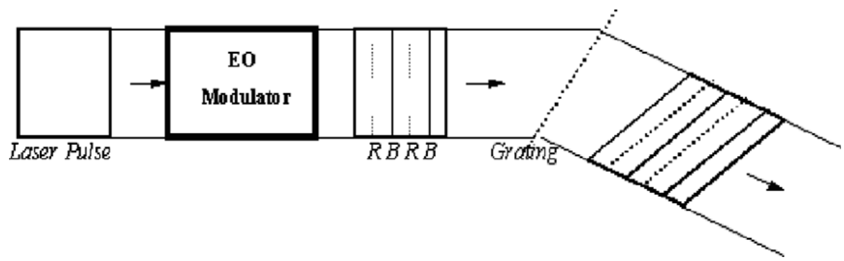

Fig. 2. The scheme of SSD.

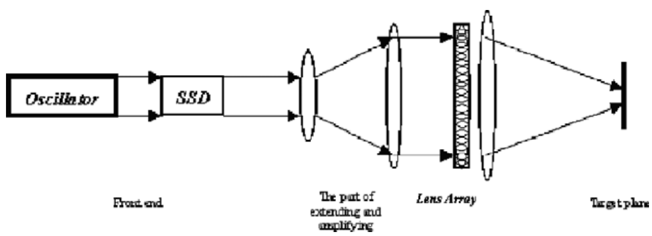

Fig. 3. A schematic of the combining LA with SSD in laser system.

3. Simulated results and experiments

The simulation is based on Eqs. (8) and (9) and only one dimension is considered. In the system design, the wavelength λ and the pulse width are 1.053 μm and 1 ns, and the designed size of focal pattern, the maximum beam aperture D_0 incident to grating, the maximum beam aperture D incident to LA and the focal length are 0.6, 35, 350 and 750 mm. The aperture and the focal length of elementary lens are 31.8 and 39772.7 mm, and grating dispersion $\frac{\Delta\theta}{\Delta\lambda}$ is 297 μrad/Å. The results shown in Fig. 4 are the normalized intensity distribution of simulation considering the effect of transversal thermal conduction [10].

The Fig. 4a is beam intensity distribution on target plane only smoothed by LA, which σ_{rms} of irradiation nonuniformity is about 14%, and b–d are the results of combining SSD with LA, which σ_{rms} can fall to about 3%. The simulation shows that the application of SSD can

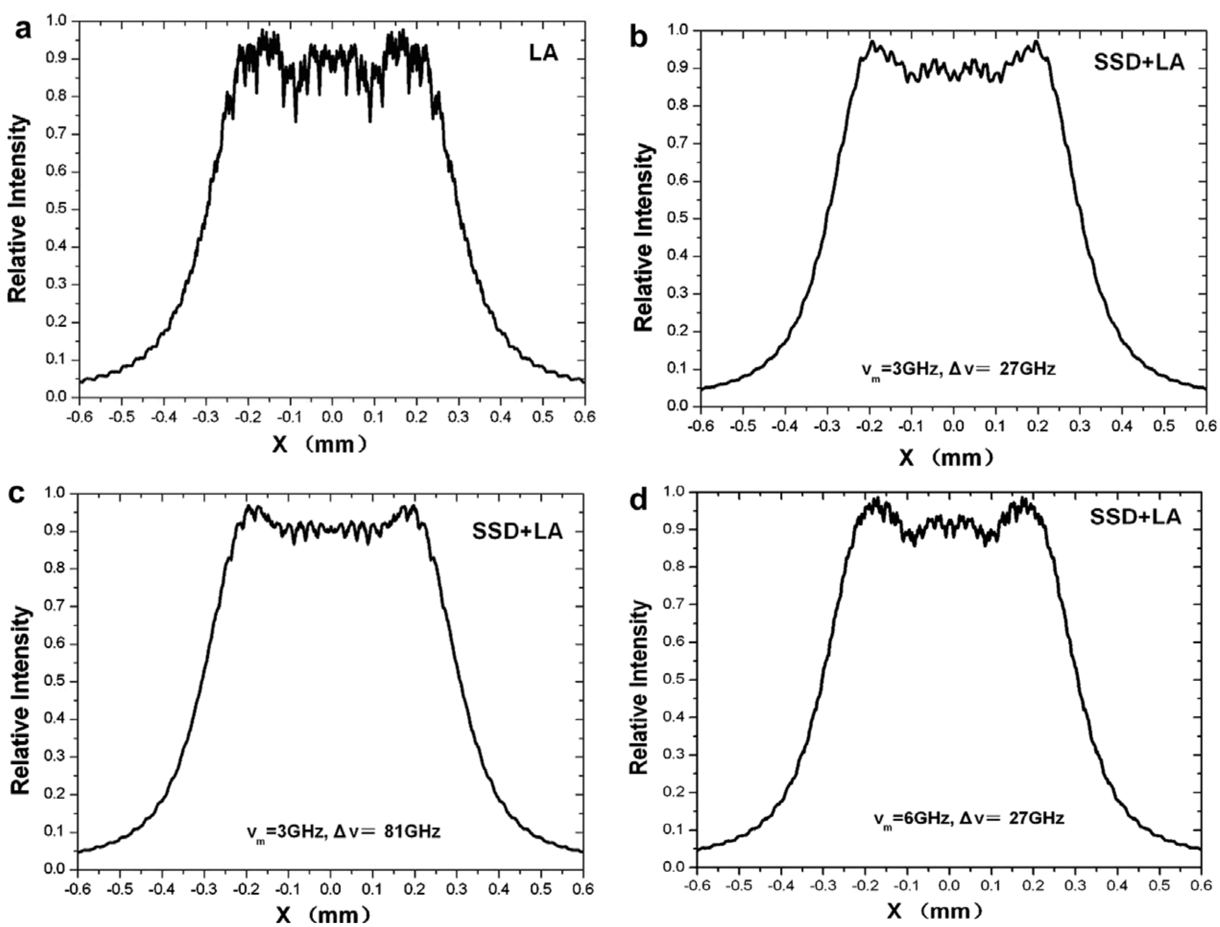

Fig. 4. The intensity distribution of simulation in target plane in different smoothing methods and parameters. (a) LA, $\sigma_{rms} = 14\%$; (b) LA + SSD, $v_m = 3$ GHz, $\Delta v = 27$ GHz, $\sigma_{rms} = 4.3\%$; (c) LA + SSD, $v_m = 3$ GHz, $\Delta v = 81$ GHz, $\sigma_{rms} = 3\%$; (d) LA + SSD, $v_m = 6$ GHz, $\Delta v = 27$ GHz, $\sigma_{rms} = 5.5\%$.

effectively smooth the irradiation nonuniformity for spatial modulation introduced by LA and hold the characters of LA, such as the flat-top and sharp-edge envelope. The effect is remarkable though LA is usually applied in irradiation uniformity of quasi-near-field, which is different from the other spatial smoothing approaches.

If the bandwidth $\Delta\nu$ of beam spectrum in SSD were added by increasing the modulating depth, the incoherence

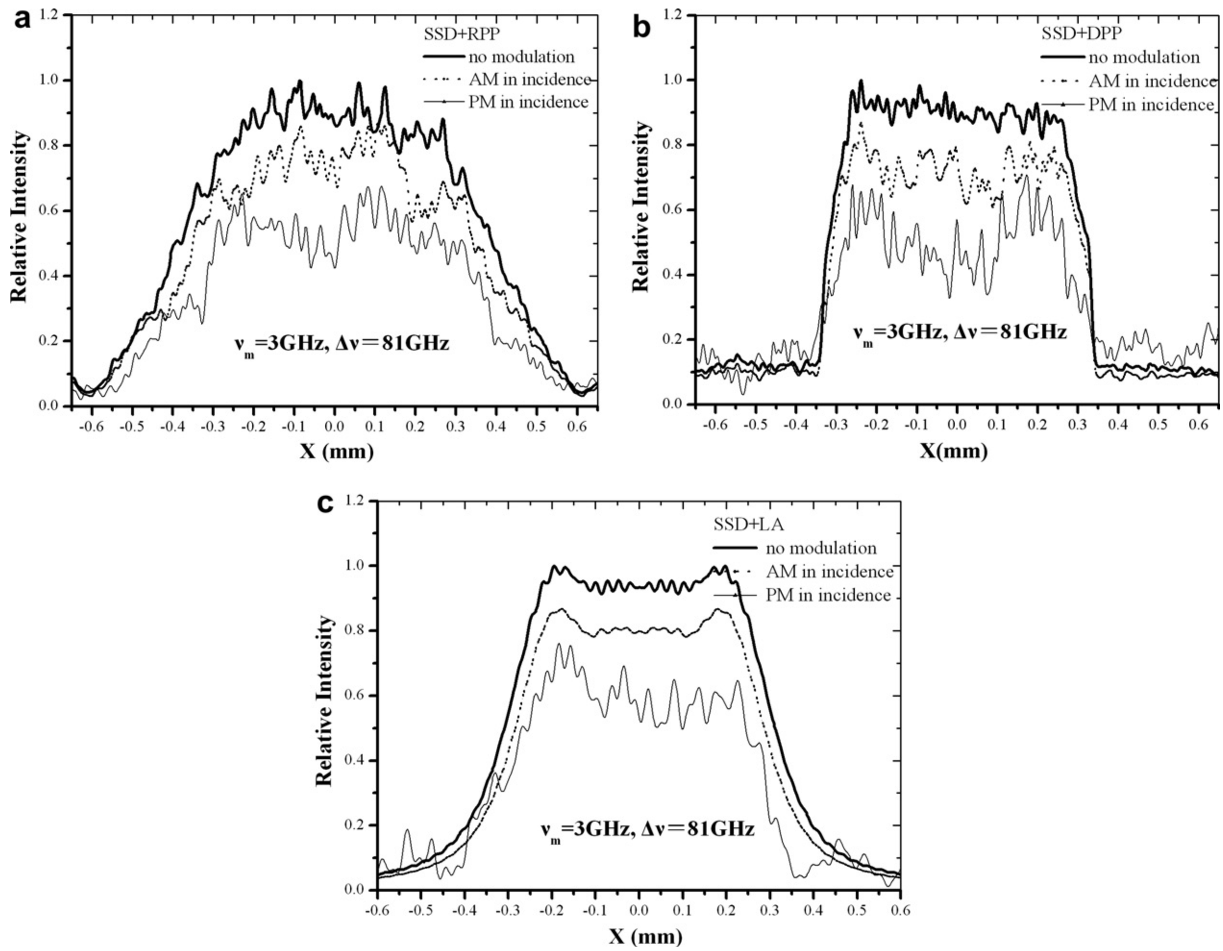

Fig. 5. The focal pattern intensity distribution of simulation in different smoothing methods when distortion of incidence considered, with the modulating frequency of 3 GHz and the spectral width of 81 GHz in SSD. The AM in incidence is the result of a 6th-order supper-Gaussian beam propagation with Fresnel number of 10, and the PM is described by Eq. (10). (a) SSD + RPP (b) SSD + DPP (c) SSD + LA.

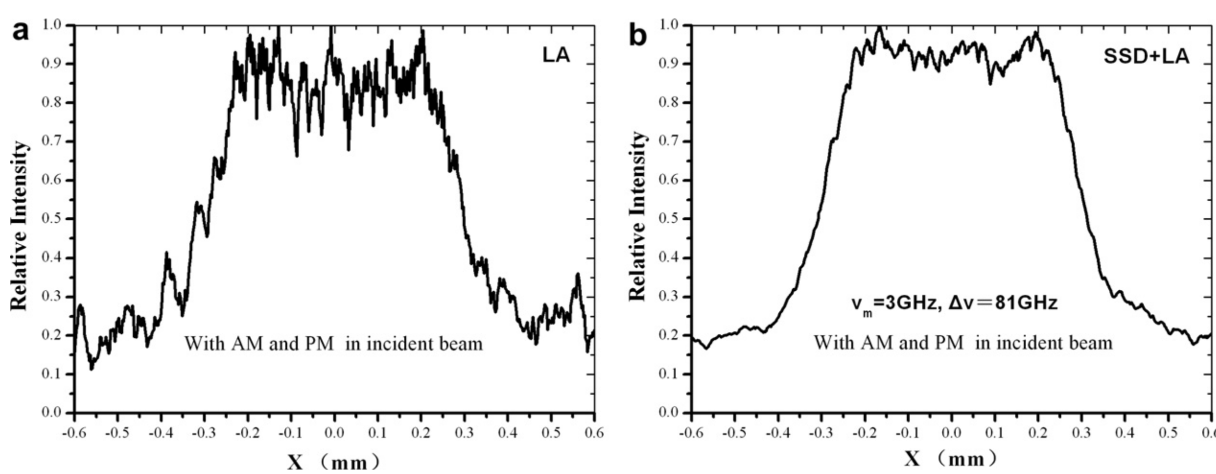

Fig. 6. The intensity distribution of simulation when both amplitude modulations and phase aberrations in incident beam considered. (a) Smoothing by LA without phase modulation, $\sigma_{rms} = 20\%$, (b) smoothing by LA + SSD, $\nu_m = 3$ GHz, $\Delta\nu = 81$ GHz, $\sigma_{rms} = 7.6\%$.

of the beam would be added too. Both the beam spectral divergence $\Delta\theta$ and sub-pattern shift Δl are enlarged too, which lead to the spatial modulations with scales low than Δl in focal pattern smoothed, as shown in Fig. 4b and c.

The relationship between the uniformity and the modulating frequency ν_m which is basic feature in the application of SSD [5] can also be analyzed from Fig. 4b and d. The increasing of ν_m not only speeds up the moving of sub-patterns in focal plane which can improve irradiation uniformity, but also enhance the coherence of beam, bring about interference fringe pattern due to the fast "color cycling". It is very important to adopt the suitable parameters of SSD while a more smoothing beam profile is required.

The incident wavefront is also important for any smoothing method because variations of wavefront such as AM or PM may reduce irradiation uniformity on target plane. However, during the course of beam propagating in

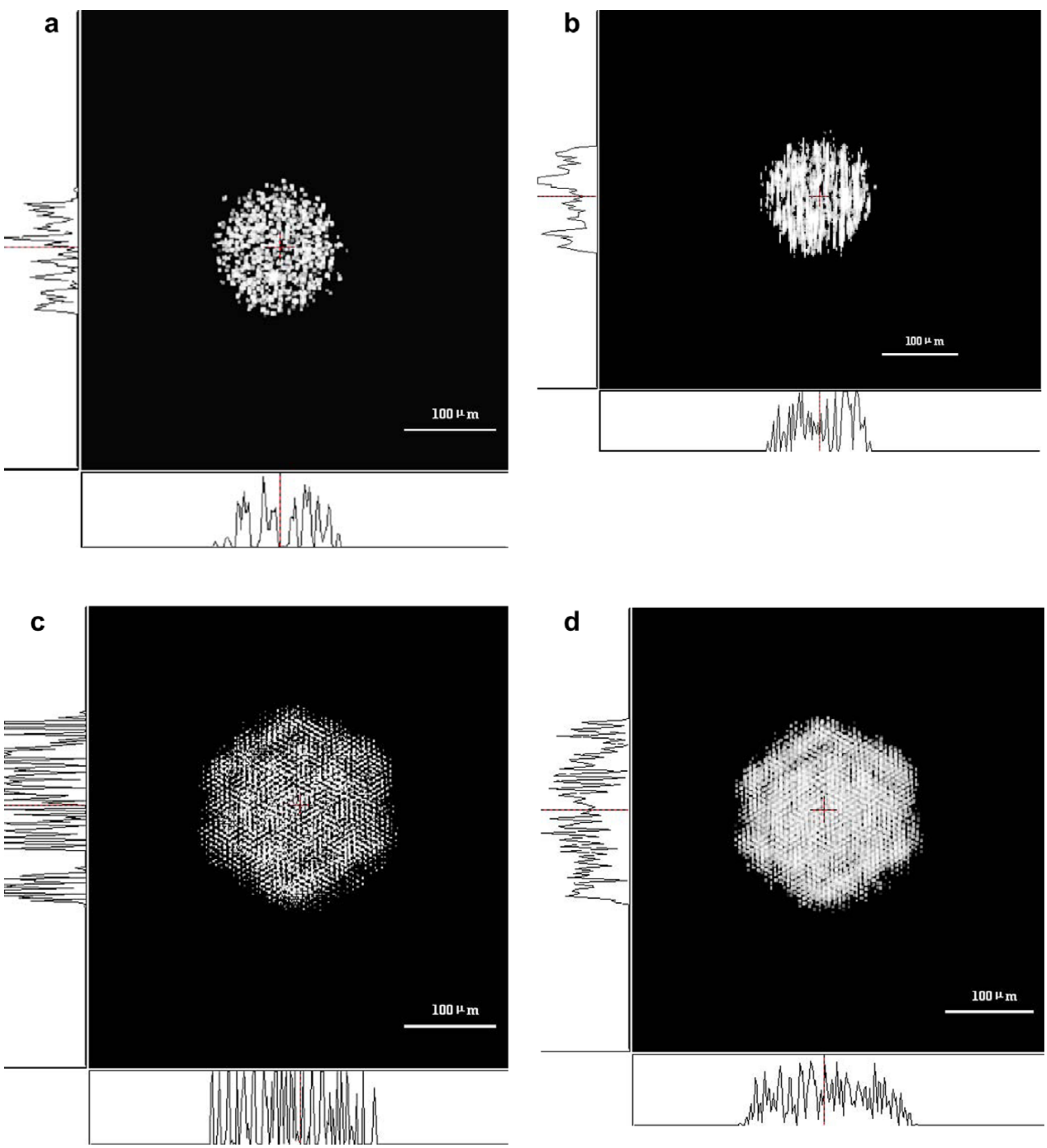

Fig. 7. Measured IR (1.053 μm) images of 2 ns laser pulse. (a) DPP without phase modulation, (b) DPP with 1-D SSD (in Y-direction) at $\Delta\nu \approx 37$ GHz, (c) LA without phase modulation, (d) LA with 1-D SSD (in Y-direction) at $\Delta\nu \approx 37$ GHz. The number of DPP element is 512×512, and of LA is 7×6. As demonstrated with line distributions through the center of the image in horizontal (X) and vertical (Y) direction, the patterns have a smooth spatial intensity envelope in the direction of SSD. For the incidence is not a plane wave as the requirements in the design, there are some modulations in the measured patterns.

a laser system, the spatial intensity distribution will be gradually changed due to diffraction. Furthermore, the optical fabrication errors of hundreds of optical elements in high power laser system will also lead to phase distortion, resulting in most modulation of the beam. These errors can be divided into three kinds according to their spatial "wavelength" [11]: (1) surface deviation with low spatial wavelength which affects the beam focusable power and the profile of focal spot, and (2) ripple error with middle spatial wavelength, such as between 0.12 mm and 33 mm, that can induce a rapid increasing of middle-frequency modulation of beam profile which may causes beam nonlinear propagation, and (3) roughness with very shot spatial wavelength, such as lower than 0.12 mm, that may also lower the damage threshold of optical film. However, the effect of roughness can be reduced by the usage of spatial filter. According to Fourier analysis method, a complex phase modulation (PM) induced by fabrication errors in a high power laser system may be expanded in a trigonometric series of different spatial wavelength:

$$\phi_{\mathrm{PM}}(x) = \frac{2\pi}{\lambda}\sum_{n}\delta_n \sin(2\pi x/L_n), \tag{10}$$

where δ_n and L_n are amplitude and wavelength of phase modulation induced by different fabrication errors.

In LA design the requirements of incident beam are weaker than in other spatial smoothing approaches [3], so is in the using of SSD and LA. Some numerical simulations are made comparing with RPP and SSD, DPP and SSD, as shown in Fig. 5. The AM in simulations is the result of a 6th-order supper-Gaussian beam propagating with Fresnel number of 10, and the PM is described by Eq. (10) added to a 6th-order supper-Gaussian beam, in which the typical wavelengths of 0.12 mm, 2.5 mm, 8.3 mm, 33 mm, 100 mm and 350 mm with corresponding amplitude of $\lambda/20$, $\lambda/10$, $\lambda/4$, 2λ, 5λ and λ are considered according to the parameters of simulation and reference [11]. The results show that the focal pattern of RPP and SSD can keep the basic spatial profile when distortion in incidence considered, but is hard to get a flat-top and sharp-edge envelope. And in the case of DPP and SSD, a satisfied focal pattern as the design can be gotten, changes of incident beam also may lead to high modulation in the focal pattern because the design of DPP is very strict with incidence, especially the incident phase distribution. But in the focal pattern of LA and SSD, there is less distortion than of DPP and SSD when AM or PM considered, and an approximate flat-top and sharp-edge profile can be maintained. Further more, the irradiation uniformity will still be improved in that case if LA is used with SSD, and the σ_{rms} will decease from 20% to 7.6%, seen in Fig. 6. It also shows that the tolerance of incidence is enhanced in the designing and the implementing of LA and SSD.

Measured IR images (measured by 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 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 obviously 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 was the results of hard-edge diffraction of the elementary lens and less of elements numbers, and it can be more smoothing with SSD. In experiments the incident beam was not a plane wave as the design require but a 6th-order supper-Gaussian beam 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. 7d and the spatial profile is more flat.

4. Conclusion

A method of combining LA with SSD has been proposed to improve the beam irradiation uniformity on target plane. The effect of smoothing is related to the parameters of SSD though the basic profile of focal pattern is depended on the design of LA. The advantage of this method is that not only a smoothed focal pattern but also an approximated flat-top and sharp-edge profile can be got when there is distortion in incidence different from the original design, while the technology of SSD with other spatial smoothing method such as RPP and DPP [8] usually cannot get a far-field pattern like that in that case. Though there are some high modulations in the focal pattern caused by the hard-edge diffraction of elementary lens, it can be improved by apodized LA designing.

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