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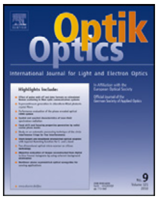

Diffraction of a modulated laser beam in 3ω optics system

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ABSTRACT

Based on diffraction optical theory, diffraction of a laser beam with periodic amplitude modulation and phase distortion is derived in 3ω optics system. Influence of defocus distance and focal length of a focusing lens on intensity distribution of diffraction light is investigated by numerical simulation. The results show that appropriate distance away from the focus spot and increase the focal length in final optical systems are beneficial to control the modulation of light intensity fluctuations and reduce the optical components damage caused by small-scale self-focusing effect.

1. Introduction

In a high power laser system utilized for Inertial Confinement Fusion (ICF) research, laser-induced damage of optical components has been the bottleneck of the optical systems to improve energy density [1–3]. Wave-front of a laser beam is always affected in process of transmission and amplification by amplitude and phase modulation generated by defects of optical elements, small-scale spatial noise, air turbulence and so on [4,5]. Both spatial filtering and adaptive deformable mirror can't effectively control modulation ripple with middle spatial modulation period between 0.1 mm and 8 mm. When a modulated laser beam gets through final optical systems, the fastest increasing frequency and the fastest increasing factor in 3ω optics system is triple of 1ω optics system [6]. This laser beam with enhanced modulation focused by the focusing lens, due to high power small-scale self-focusing and laser light scattering, will result in serious laser damage of fused silica used in color separation gratings (CSGs) and debris shield (DS).

In final optical systems of ICF driver, laser damage in fused silica not only reduce life time of components, increase operating costs for high power laser devices, but also seriously affect stability and far-field beam quality of a high power laser system. Therefore it is need to control laser beam near-field distribution pattern and optimize structures of final optics assembly to decrease optical components damage caused by noise.

In this paper, evolution of diffraction distribution for a laser beam with amplitude modulation and phase distortion focused by a focusing lens is analyzed theoretically based on optical diffraction theory. Numerical simulations mainly discuss the effect of noise with middle spatial frequency on the laser beam. Influence of defocus distance and focal length of the lens on intensity distribution pattern of diffraction light are presented. The results provide reference to reduce laser damage and effectively control beam quality.

2. Theory

In a high power laser system, the typical final optical system is composed of nonlinear frequency conversion crystals, a final focusing lens, CSGs and a main DS and so on, as shown in Fig. 1.

We assume that the final focusing lens is an ideal one, and lens aperture is large enough to ignore additional diffraction caused by finite aperture. According to diffraction integrate theory, the field of output light at defocused distance Δf before focal spot is given by

$$U(x,y)=\frac{\exp[ik(f-\Delta f)]\exp[(i\pi/\lambda(f-\Delta f)(x^2+y^2)]}{i\lambda(f-\Delta f)}\times\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}U_{in}(x_0,y_0)\times\exp\left[\frac{ik\delta f}{2(f-\Delta f)}(x_0^2+y_0^2)\right]\times\exp\left[\frac{ik}{(f-\Delta f)}(x_0x+y_0y)\right]dx_0dy_0 \quad (1)$$

where U_{in} (x_0,y_0) is the complex amplitude of entrance laser beam, λ is the incident beam wavelength, f is the focal length of the lens, and $\delta f=\Delta f/f$.

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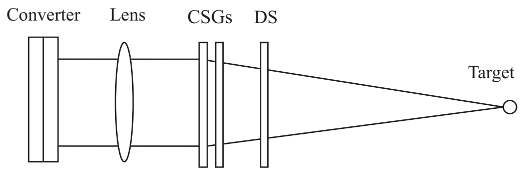


Fig. 1. Schematic of a final optical system.

The intensity distribution of output light is given by

$$I(x,y)=\frac{1}{\lambda^2(f-\Delta f)^2}\left|\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}U_{in}(x_0,y_0)\times\exp\left[\frac{ik\delta f}{2(f-\Delta f)}(x_0^2+y_0^2)\right]\exp\left[\frac{ik}{(f-\Delta f)}(x_0x+y_0y)\right]dx_0\,dy_0\right|^2 \tag{2}$$

In practice, the incident laser beam is always affected in transmission by amplitude modulation and phase distortion generated by defects of the optical elements, small-scale spatial noise, and air turbulence and so on. In a nonlinear propagation system, noise can't be separated from the entrance beam and we will need to solve the coupled paraxial wave equations. In some Lawrence Livermore National Laboratory (LLNL) research reports, in order to obtain a clear physical image of noise diffraction, the small-signal noise is separated from the entrance beam by the small-signal approximation and an equivalent matrix of a nonlinear amplification system. The physical model can describe propagation properties of noise signal with different spatial frequencies in a nonlinear system and become the basis of the physical analysis for the root-mean-square gradient and power spectral density in a large aperture high power laser system [7,8]. Thus, the electric field of entrance light with noise under the small-signal approximation can be given by

$$U_{in}(x_0,y_0)=U'_{in}(x_0,y_0)[1+U_n(x_0,y_0)] \tag{3}$$

where $U'_{in}(x_0,y_0)$ is the super-Gaussian beam in the objective plane of lens. U_n (x_0,y_0), which is the noise perturbations with both periodic amplitude modulation and phase distortion, can be expressed as

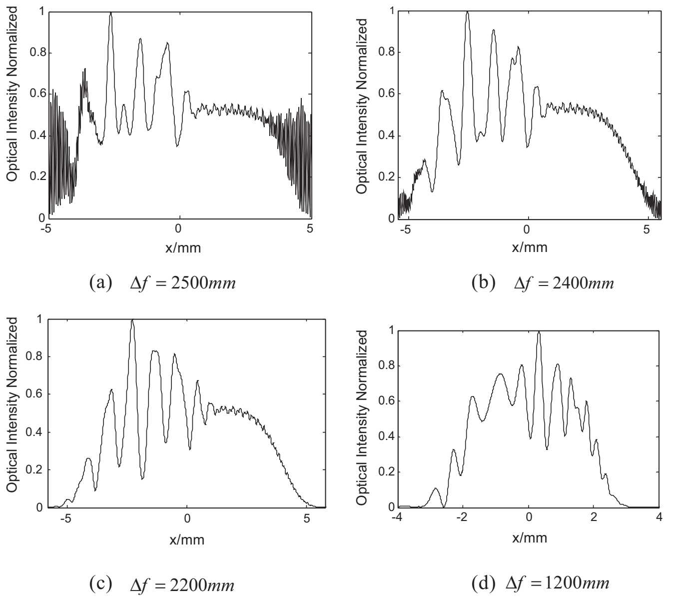
$$U_n(x_0,y_0)=\sum_i\sum_j A_{a_i}[\sin(x_0 2\pi/l_{a_i})\sin(y_0 2\pi/l_{a_i})]\times\exp[iA_{p_j}[\sin(x_0 2\pi/l_{p_j})+\sin(y_0 2\pi/l_{p_j})]] \tag{4}$$

where A_{a_i} and l_{a_i} are the peak and period of the ith amplitude modulation, respectively; A_{p_j} and l_{p_j} are the peak and period of the jth phase modulation, respectively.

According to Eq. (2), the second phase factors induced by defocus distance and noise make additional interference superposition of sub-beam in the defocus plane. Therefore, the spatial diffraction pattern of near field before focal spot is various with defocus distances. Substitute Eqs. (3) and (4) into Eq. (2), we can numerically simulate fluctuate light intensity distribution at different distances from the focal plane.

3. Simulation and results

A laser beam propagating in a high power laser system generally has a super-Gaussian intensity profile. Assuming the incident light field is sixth-order super-Gaussian beam, we can calculate intensity distribution of diffraction field at different defocus distances. We choose incident beam wavelength $\lambda = 1.053\ \mu$m, the lens focal length $f = 3296$ mm and object distance $d_1 = 200$ mm. The initial beam profile is a sixth-order super-Gaussian with a sinusoidal modulation period of $l_{a_i}=l_{p_j}=1.5$ mm and a modulation amplitude of $A_{a_i}=A_{p_i}=0.5$.



(a) $\Delta f = 2500mm$ (b) $\Delta f = 2400mm$

(c) $\Delta f = 2200mm$ (d) $\Delta f = 1200mm$

Fig. 2. Near field intensity distribution of beam at different positions.

In order to quantitatively depict near field beam quality, modulation contrast ratio R, which is introduced as a characteristic parameter of the spatial modulation in the near field, is given by

$$R=\left[\sum_{i=1}^{N}\left(\frac{(I_i-\sum_{i=1}^{N}I_i/N)^2}{N}\right)\right]^{1/2}. \tag{5}$$

In this paper, simulation is solely performed along the x-axis. Fig. 2 shows intensity distribution pattern of a laser beam with noise at different defocus positions before focal spot. A large number of high frequency modulation components strengthen light diffraction fluctuation and destroy the near field beam quality at the positions of 0.75f (2500 mm) and 0.36f (1200 mm) away from lens focus. On the contrast, light intensity distribution is smoother between the two planes. Thus, it shows that appropriate defocus distance suppresses interference superimposition of wave-front sub-beams, reduce intensity modulation of diffraction wave and risk of laser damage for fused silica induced by small-scale self-focusing. In the high power laser system, the simulation results show that less intensity modulation can be obtained for lens with a fixed focal length by selecting an appropriate defocus distance. Therefore the effect of amplitude and phase modulation of a laser beam on optical components functional damage can be effectively suppressed by optimizing structure in a final optical system.

Lens focal length longer results in larger radius of curvature of modulation divergent beam induced by the receiving plane away from focal spot as shown in Eq. (2). Therefore, fluctuation of intensity distribution before focus can be reduced by increasing focal length of final focusing lens. The influence of the focusing lens with different focal length on the diffraction beam intensity distribution away from focus is numerical simulated by inputting the same entrance light field, as shown in Fig. 3. The results indicate that modulation contrast ratio of diffraction lights before focal spot reduces as focal length increasing. This conclusion is consistent with the previous theoretical prediction. In addition, there always exists a near field intensity modulation minimum at a certain position before focus for lenses with various focal lengths. The defocus distance of the receiving plane with the minimum value of near field intensity modulation increases as focal length growing. The spatial range of smooth regions of near field with intensity modulation is enlarged and the modulation contrast ratio is reduced

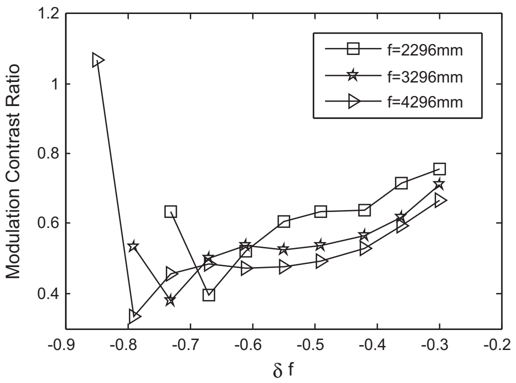


Fig. 3. Optical field distribution for focusing lens with different focal lengths.

by increasing focal length of the final focusing lens. Therefore, we can suppress light intensity fluctuation and decrease risk of laser damage in fused silica by optimizing structure parameters of final optics components in a high power laser system.

4. Conclusion

Diffraction characteristic of a laser beam with noise getting through a focusing lens is obtained by diffraction integrate theory in a final optical system. Both theoretical analysis and numerical simulation results show that diffraction patterns superimposed by wave-front sub-beams at various distances before focal spot appear different spatial distribution due to additional second phase factors induced by defocus distance and noise. As a result, we can change spatial position of optical elements for final optical components in high power laser systems to avoid laser damage induced by intensive noise signal which can't be suppressed by spatial filter. In addition, lens with long focal length for a laser beam with noise can decrease diffraction intensity modulation fluctuation before focus and prevent fused silica laser damage caused by middle and low frequency phase perturbation. Therefore, it is important to optimize construction design of final optical components for enhancing output energy in high power laser systems.

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