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Analysis and optimization of radial smoothing based on optical Kerr effect for irradiation improvement

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ABSTRACT

In radial smoothing scheme, taking a super-Gaussian pulse train obtained by the pulse stacking scheme based on fibers and spatial shaping technology based on serrated-aperture apodizers as the pump laser, due to the hemispherical shape of the optical Kerr medium, the induced refraction index by the interaction of the optical Kerr medium and the pump laser is spherically distributed with periodical variation. Consequently, the transmission wavefront of the laser quads in the beamline is periodically modulated, resulting in the rapidly and periodic focal zooming in far field. This focal zooming smoothes the speckles on target plane in the radial direction in the sense of averaged over a finite time interval. The performance of the pump laser and the optical Kerr medium strongly affect the radial smoothing effect. In order to obtain better smoothing effect as that of smoothing by spectral dispersion, the propagation model of laser quads in the beamline with the radial smoothing scheme has been built up and further used to optimize the parameters of the pump laser and the optical Kerr medium. The beam smoothing effects of the joint use of continuous phase plate and polarization control plate with smoothing by spectral dispersion, as well as radial smoothing have been analyzed and compared in detail. Results indicate that, the delay time between each super-Gaussian pulse in the pump laser should be matched with the pulse width of each super-Gaussian pulse to achieve the best and stable radial smoothing effect, while the fluctuation of the peak intensity of each super-Gaussian pulse in the pump laser would degrade the radial smoothing effect. The selection of the optical Kerr medium directly determines its thickness and peak intensity of the pump laser to obtain the required wavefront modulation, which affects the feasibility of the radial smoothing scheme.

1. Introduction

In laser-driven inertial confinement fusion (ICF) facilities, the precise control of intensity distribution of laser beams on target is highly required in physical experiments [1]. Varieties of laser-beam smoothing techniques including the space and time-domain beam smoothing techniques have been studied and applied [2]. The space-domain beam smoothing techniques involves random phase plate (RPP), continuous phase plate (CPP), lens array (LA), kinoform phase plate (KPP), polarization control plate (PCP), etc [3]. The time-domain beam smoothing techniques contains induced spatial incoherence (ISI), smoothing by spectral dispersion (SSD), etc [4]. In order to improve the irradiance uniformity of the laser beam on the target plane as well as possible, several beam smoothing techniques are implemented simultaneously in practical applications [5]. For instance, the beam smoothing scheme has been implemented by the joint use of SSD, CPP and PCP in National Ignition Facility (NIF) [6], and the longitudinal spectral dispersion method and CPP are both implemented in Laser Megajoule (LMJ) [7]. However, the smoothing direction of the one-dimensional SSD was along the dispersion direction of the grating, leading to the striping pattern inside the focal spot [8]. The dispersion directions of two-dimensional SSD were arranged to be orthogonal to each other by two pairs of modulators and gratings, resulting in the interference between the laser beams in target plane. Furthermore, an integral time of nearly a hundred of picoseconds is required to obtain the best as well as stable smoothing effect for both one-dimensional and two-dimensional SSD [1,4,8]. In order to overcome these defects of SSD, we proposed a radial smoothing (RS) technique based on the optical Kerr effect [9]. Taking a super-Gaussian pulse train generated by the pulse stacking scheme based on fibers and spatial shaping technology based on serrated-aperture apodizers as the pump laser [10], due to the hemispherical shape of the optical Kerr medium, the induced refraction index of the optical Kerr medium is spherically

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distributed with periodical variation. The compensating medium counteracts the phase generated by the OKM of linear refractive index. When the periodic spherical wavefront modulation is added to the laser beam in the beamline, the spherical wavefront leads to the periodical variation of the focal-spot size, i.e., focal zooming [11]. This focal zooming yields the radial move of the interference pattern on target plane, and further smoothes the intensity distribution of focal spot in the radial direction in the sense of averaged over a finite time interval. Meanwhile, the cross and overlapping of laser beams decrease due to the fast focal zooming, suppressing the cross-beam energy transfer to a certain extent [11].

In the representative ICF facilities like NIF, the fundamental grouping of eight beams in the laser bay is called a bundle. In the switchyard, each bundle is split into two sets of four beamlets or a quad, with one quad from each bundle directed toward the top and bottom of the target chamber [12]. In order to analyze the radial smoothing effect of the laser quads, the propagation model of laser quads based on the RS scheme has been built up.

In the reference [9], the feasibility of the radial smoothing scheme was mainly analyzed. In the reference [13], the choice of the optical Kerr medium (OKM) was discussed and the characteristics of the radial redistribution on the radial smoothing effect were also simulated and analyzed. However, it is found that the fluctuation of the radial smoothing effect with the integral time would exist since the parameters of the pump laser and the OKM have significant influence on the radial beam smoothing effect in the RS scheme. Meanwhile, the radial smoothing performance would be degraded due to self-focus effect of the pump laser with the thick OKM. To achieve the same smoothing effect as that of SSD, the scheme of the radial smoothing has been improved, and the parameters of the pump laser and the OKM have been analyzed and optimized by using the established propagation model. Finally, the beam smoothing effect of the "1D-SSD+CPP+PCP" scheme and RS scheme have also been simulated and compared.

2. Theoretical model

In order to avoid obvious impact on the propagation and the amplification of the laser quads, the optical Kerr medium is inserted in the front-end of the beamline, between the pre-amplifier and the main amplifier, as shown in Fig. 1. The laser beam output from the pre-amplifier module propagates through the optical Kerr module, and its transmission wavefront tends to modulated periodically with the intensity variation of the pump laser at the same pace. Then the laser beam successively propagates through the main amplifier, frequency conversion, continuous phase plate and other elements, and is finally focused on the target plane by the lens. The wavelength of the pump laser is different from that of the laser beam (for instance, 800 nm). A dichroic beam combiner introduces the pump laser to the beamline, and a filter that could be a polarization rotation plate or a spatial filter is used to filter out the pump laser. It's worth pointing out that, the duration of the laser beam is nanoseconds level, while the duration of the pump-laser pulse is picoseconds level, and the irradiance uniformity of the target plane is a result of about dozens of picoseconds with the time-averaged intensity. Therefore the pump laser propagates through the optical Kerr medium with the laser beam synchronously at picoseconds level.

However, as the thickness of optical Kerr medium (such as CS_2) and the peak intensity of pump laser further increase, the radial smoothing performance would be degraded due to self-focus effect of the pump laser. In order to avoid an obvious impact caused by the self-focus effect, by using the spatial shaping technology based on serrated-aperture apodizers, the Gaussian pulse is shaped to the super-Gaussian pulse. To obtain the enough periodic spherical wavefront modulation, the optical Kerr medium is processed to hemispherical shape or the optical Kerr medium is filled in a hemisphere container. A filter is used to filter out the pump laser. The compensating medium is used to counteract the phase generated by the linear refractive index (n0) of the OKM.

Each laser beam is independently wavefront modulated, amplified, frequency converted, polarization rotated, and finally focused on the target plane. The polarization of the four beamlets in one quad is orthogonal to each other due to the function of PCP, thus the light fields of the four beamlets are expressed as [1].

$$\vec{E} = \sum_{m=1,-1}\sum_{n=1,-1} A_0\left(1+2\pi\sigma_a\left[\sin\left(\frac{2\pi x_m}{l_x}\right)+\sin\left(\frac{2\pi y_n}{l_y}\right)\right]\right)\exp\left[-\left(\frac{x_m^{2N}}{w^{2N}}+\frac{y_n^{2N}}{w^{2N}}\right)\right]$$
$$\exp\left\{i\left[\varphi(x_m, y_n)+\phi_{cpp}+\varphi_m\right]\right\}\left(\left|\frac{m+n}{2}\right|\vec{e}_x+\left|\frac{m-n}{2}\right|\vec{e}_y\right) \tag{1}$$

where $x_m = x - mw$, $y_n = y - nw$, w is the beam width, σ_a is the modulation depth, l_x and l_y are the modulation interval, respectively. ϕ_{CPP} is the phase correction of CPP, $\vec{e}_x$ and $\vec{e}_y$ are polarization of laser beam. φ and φ_m are the initial wavefront distortion and the additional wavefront of the laser beam induced by OKM and compensating medium, the initial phase distortion was constructed by the model of gaussian random phase screen [14] i.e.,

$$\varphi(x_m, y_n) = \sigma_l \mathrm{random}(-1, 1) \otimes \exp\left[-\left(\frac{x_m^2}{g_x^2}+\frac{y_n^2}{g_y^2}\right)\right] + \sigma_h \mathrm{random}(-1, 1) \tag{2}$$

where σ_l and σ_h are the ranges of the low frequency and the high frequency, respectively. g_x and g_y are the fluctuation intervals in x and y direction, respectively.

As the pump laser of a super-Gaussian pulse train obtained by the pulse stacking scheme based on fibers and spatial shaping technology based on serrated-aperture apodizers, due to the hemispherical shape of the optical Kerr medium, the induced refraction index by the interaction of the optical Kerr medium and the pump laser is spherically distributed with periodical variation. The compensating medium counteracts the phase generated by

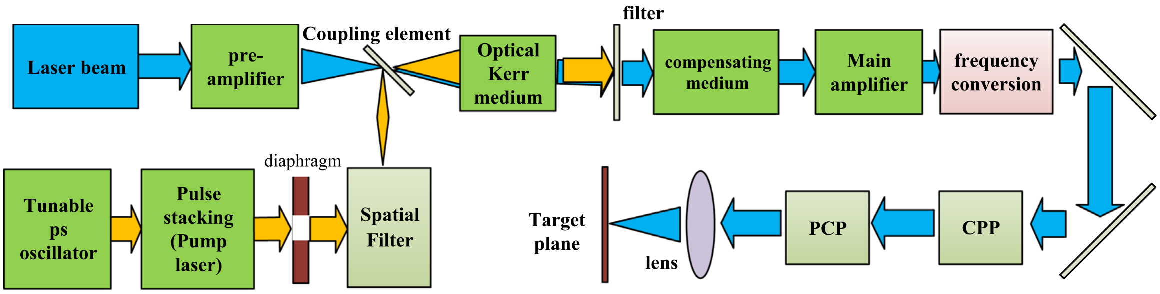

Fig. 1. Schematic illustration of RS in the beamline.