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Control over high peak-power laser light and laser-driven X-rays

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ABSTRACT

An optical system was demonstrated that enables continuous control over the peak power level of ultrashort duration laser light. The optical characteristics of amplified and compressed femtosecond-duration light from a chirped-pulse amplification laser are shown to remain invariant and maintain high-fidelity using this system. When the peak power was varied by an order-of-magnitude, up to its maximum attainable value, the phase, spectral bandwidth, polarization state, and focusability of the light remained constant. This capability led to precise control of the focused laser intensity and enabled a correspondingly high level of control over the power of an all-laser-driven Thomson X-ray light source.

1. Introduction

High-peak-power laser systems have undergone rapid progress recently, enabled by the development of various techniques including chirped pulse amplification (CPA) [1], optical parametric chirped pulse amplification (OPCPA) [2], and the availability of high quality large diameter amplifier gain media [3–5]. Based on these advances, several petawatt (PW) peak-power laser systems are now operational [6–8], and a number of multi-PW systems are under construction. In turn, these laser advances are facilitating rapid progress in research and development in the emerging area of high-field science, including fundamental studies of the interactions of light with matter at ultra-high intensity levels [9], as well as the development of ultra-high-gradient charged-particle accelerators [10,11], high-brightness X-ray light sources [12,13], and high-flux neutron sources [14,15].

Progress in high-field science and technology development depends not only on the ability to generate high peak-power laser light but also on the ability to focus that power to ultra-high intensity [16] and control the level of that intensity continuously [17]. For example, the signatures of nonlinear and quantum effects in high-field scattering experiments are found by identifying subtle correlations between the input laser intensity and the output X-ray and electron parameters [18]. Laser-driven electron and ion accelerators [19], as well as X-ray sources, are each optimized at specific and well-defined laser intensity levels.

Several techniques have been implemented to focus laser light of a given peak power to its highest intensity level. For instance, deformable mirrors with active feedback control loops are now used to correct any spatial phase imperfections in the laser beam that were acquired during amplification. In addition, to avoid additional phase distortions generated when high peak-power light propagates through refractive media, only reflective optics are used under vacuum after amplification and pulse compression. In prior work, all attenuation systems, designed to adjust the laser intensity level on target continuously, have invariably required the use of refractive optics. In this work, we present a simple and novel optical system that overcomes this problem. We show that it is able to attenuate the peak power of laser light in a continuous and controllable way while preserving spectral and spatial fidelity nearly ideally. The spectrum, spatial phase-front, and polarization of the attenuated pulses remain unchanged even as the peak laser power is varied—over a dynamic range that extends over an order-of-magnitude, up to the maximum attainable power level. Additionally, we showed the importance of this control over the laser intensity by demonstrating that it enables us to control the power of a recently developed laser-driven X-ray light source [13], which may prove to be useful for low-dose radiological applications.

Numerous methods are used to vary the energy of laser beams. The simplest and most common way is to place neutral density filters in the amplified beam, which only permits the variation of the energy in large discrete steps. For continuous variation of energy, a combination of a half-wave-plate (HWP) and polarizer is used. The use of such refractive optics is limited to low-power laser pulses due to B-integral effects and the low damage threshold of the associated optics. The output energy of a laser amplifier can also be varied by varying the energy of the seed

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or pump beam as well as by changing the timing between them [20]. In the latter scheme, the output energy is reduced by operating the amplifier away from its optimal point, resulting in large fluctuations of the laser output energy as well as a change in the temporal contrast. We previously implemented a device consisting of a zero-order half-wave plate (ZHWP) and broadband thin film polarizers (TFP) [21] used to control the output energy at the exit of the amplifier. This has been shown to have excellent characteristics with regard to precise control of the laser energy. However, the polarizers that are used require an incident angle of ~72° to support the laser spectrum and minimize dispersion [22]. This large angle of incidence leads to the requirement that the TFP be >4 times the size of the incident beam. This requirement is not practical for PW-level laser systems, where the beam size can be 10 cm or even larger depending on the energy of the beam. The thickness needs to be small to keep B-integral induced distortion of the beam to a minimum. Such optics are expensive and difficult to manufacture.

Other methods exist to adjust the energy level of a high-power chirped-pulse-amplified laser, either during or after pulse compression. For example, clipping the spectrum between the two gratings in the pulse compressor will lower the energy but also lengthen the pulse duration, whilst aperturing the high-energy beam will reduce the energy, but also change the confocal parameter. The intensity of the interaction could also be changed without changing the energy, by adjusting the focal position, relative to the target, but beam collimation would also change. The interaction intensity could also be changed by changing the arrival time delay of the pulse relative to that of a target that was moving (such as the electron pulse used in our experiment). Yet, when the target has a duration comparable or even shorter than the laser pulse itself, as is the case in our experiment, then other parameters of the interaction (scattering in our case) will also change (such as the amount of electron charge with which the laser pulse interacts). Ideally, for controlled parametric studies, only a single parameter should be changed at a time, and all others should be kept constant.

We have therefore developed a new method for controlling the energy of the amplified pulse at the output of a high-energy, short-pulse, chirped-pulse-amplified laser system. It relies on the use of a ZHWP to rotate the polarization of the incident laser pulse and the (grating) pulse compressor as the polarizing element. Compared to prior work [23], we find that use of a ZHWP results in negligible spectral modulation as well as minimal distortion due to B-integral effects. By using this method, we can change the pulse energy alone, and keep all other parameters constant, such as the focused spot size and pulse duration. This controlled variation in the output energy is applied to controlling the fluence of X-rays produced by the interaction of a high-power laser pulse with a high-energy laser-driven electron beam.

2. Theoretical model

For the type of laser system discussed in this paper (high-power, ultrashort duration), the large spectral bandwidth of the laser pulse is an important consideration in the performance of the attenuation system because the retardance of the waveplate depends on the wavelength as well as the order. First, we evaluated the wavelength dependent phase retardance for a zero-order waveplate. We compared this with the retardance produced by higher-order waveplates in order to compare the results reported here with prior work that used fifth-order waveplates. The dependence of the phase retardance on wavelength also impacts the polarization state of the output beam—a critical parameter in many applications of high-power laser pulses.

The phase retardance and polarization state are computed using the Jones matrix formulation. For a linear, horizontally polarized beam passing through a general rotated waveplate with phase retardance ϕ and rotation angle θ [24], the electric field of the light after passage through the waveplate, $\boldsymbol{E_T}$, is obtained by application of the corresponding Jones matrix $\boldsymbol{J_{wp}}$ to the incident electric field of the light pulse:

$$\begin{aligned}\boldsymbol{E_T} &= \boldsymbol{J_{wp}}(\boldsymbol{\phi},\boldsymbol{\theta})\cdot\begin{bmatrix}1\\0\end{bmatrix}\\ &= \begin{bmatrix}\cos\dfrac{\boldsymbol{\phi}}{2}+\boldsymbol{i}\sin\dfrac{\boldsymbol{\phi}}{2}\cos 2\boldsymbol{\theta} & \boldsymbol{i}\sin\dfrac{\boldsymbol{\phi}}{2}\sin 2\boldsymbol{\theta}\\ \boldsymbol{i}\sin\dfrac{\boldsymbol{\phi}}{2}\sin 2\boldsymbol{\theta} & \cos\dfrac{\boldsymbol{\phi}}{2}-\boldsymbol{i}\sin\dfrac{\boldsymbol{\phi}}{2}\cos 2\boldsymbol{\theta}\end{bmatrix}\cdot\begin{bmatrix}1\\0\end{bmatrix}\\ &= \begin{bmatrix}\cos\dfrac{\boldsymbol{\phi}}{2}+\boldsymbol{i}\sin\dfrac{\boldsymbol{\phi}}{2}\cos 2\boldsymbol{\theta}\\ \boldsymbol{i}\sin\dfrac{\boldsymbol{\phi}}{2}\sin 2\boldsymbol{\theta}\end{bmatrix}.\end{aligned} \tag{1}$$

The transmitted light after the waveplate is elliptically polarized in the most general case with a phase shift of $\cos(\boldsymbol{\phi}/2)$. This term is zero for a half-waveplate at the operating wavelength and away from the operating wavelength, this term is non-zero and the magnitude increases with the increase in the order of the waveplate. The phase term contributes to a change of the polarization state of a broadband laser pulse. For $\theta = 45$ deg., corresponding to a rotation of the incident polarization by 90 deg., the ratio of horizontal to vertical polarization can be computed as a function of wavelength. It can be shown that a broadband laser pulse, after passage through a half-waveplate, is no longer linearly polarized and the degree of deviation from this state increases with the increase in the order of the waveplate. For a zero order waveplate, this deviation is small (~1%) for a pulse with 100-nm bandwidth. For a higher order waveplate, this level of deviation is reached for a significantly smaller bandwidth.

The polarizing component of the attenuation system is the gratings in the pulse compressor. For our laser system, these are gold-coated, holographic gratings that have a reflectivity of ~93% for p-polarized light and ~30% for s-polarized light at 800 nm. Since the laser pulse undergoes four reflections in the compressor, the extinction ratio $T_{\mathrm{P}}/T_{\mathrm{S}} = 92.4$. The beam after passage through the ZHWP and grating compressor, in general, is elliptically polarized though the degree of ellipticity is small.

Assuming that the HWP in the energy attenuator is a perfect half-wave plate (PHWP), with rotation angle θ and input energy I_0 for calculation and comparison with the experimental results, the corresponding retardance ϕ equals $\lambda/2$ for a broadband spectrum, so the extra vector disappears. The theoretical P and S polarization energy after the PHWP from Eq. (1), is:

$$I_p = I_o\cos^2(2\theta), \qquad I_s = I_o\sin^2(2\theta) \tag{2}$$

The normalized optimized polarization beam at the exit of the compressor is:

$$I = I_o\cos^2(2\theta) + \frac{I_o\sin^2(2\theta)}{Extinction\ ratio} \tag{3}$$

The beam at the exit of the compressor is linearly polarized with a polarization angle $\mathrm{atan}((\tan^2(2\theta))/95)$, since I_{P} and I_{S} in Eq. (2) have the same phase.

3. Experimental results and discussion

We performed two sets of measurements using the 100-terawatt (TW) Diocles laser system. First, we experimentally determined the polarization characteristics of the laser pulse after the pulse compressor. This was followed by detailed measurements of the spatial and spectral characteristics. Fig. 1 shows the experimental layout. The laser was operated at the maximum output energy, and the beam was sampled using an attenuation system comprised of a ZHWP, and two TFPs [21], as well as neutral-density filters.

The polarization state of the attenuated high-energy (5 J) pulse from the laser system is purified using a thin film polarizer. This is necessary because the output of the waveplate–polarizer combination is elliptical when the attenuation of the beam is large. When the waveplate is set for maximum transmission, the beam is linearly polarized with a