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SHAPING OF PULSES IN OPTICAL GRATING-BASED LASER SYSTEMS FOR OPTIMAL CONTROL OF ELECTRONS IN LASER PLASMA WAKE-FIELD ACCELERATOR*

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Abstract

In typical chirped pulse amplification (CPA) laser systems, scanning the grating separation in the optical compressor causes the well know generation of linear chirp of frequency vs. time in a laser pulse, as well as a modification of all the higher order phase terms. By setting the compressor angle slightly different from the optimum value to generate the shortest pulse, a typical scan around this value will produce significant changes to the pulse shape. Such pulse shape changes can lead to significant differences in the interaction with plasmas such as used in laser wake-field accelerators. Strong electron yield dependence on laser pulse shape in laser plasma wake-field electron acceleration experiments have been observed in the L'OASIS Lab of LBNL [1]. These experiments show the importance of pulse skewness parameter, *S*, defined here on the basis of the ratio of the 'head-width-half-max' (HWHM) and the 'tail-width-half-max' (TWHM), respectively.

INTRODUCTION

The details of the time-envelope function of ultrashort light pulses ('pulse shape') plays a crucial role in many nonlinear optical phenomena. Two light pulses with the same full-width-half-maximum (FWHM), but having different rise- and fall-time characteristics, or amplitude modulation, can lead to vastly different results in processes where the excitation in the medium depends strongly on the instantaneous light intensity. An example is the yield and energy spectrum of accelerated electrons in a laser wake-field accelerator operating in the self-modulated (SM-LWFA) regime [1,2], where a driving pulse with a sharp leading edge will result in faster growth of the plasma wake-field, and consequently, higher energy electrons after acceleration. There are several methods of actively controlling the shape of ultrashort light pulses, such as frequency-domain filtering and spectral-to-time domain envelope transfer by using liquid crystal phase modulators [3] and acousto-optic phase and amplitude control [4]. Here we investigate the intrinsic pulse shaping behavior of the most widely used optical pulse compressor – the grating pair – with special emphasis on the pulse skewness.

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SHAPE OF ULTRASHORT LIGHT PULSES

The conventional description of the propagation and phase evolution of ultrashort light pulses is based on the Taylor series expansion of the optical phase around the center laser frequency, ω_0. The properties of ultrashort (sub-100 fs duration) optical pulses strongly depend on the higher order phase terms beyond the second order; the presence of higher order components (such as 'cubic' third order, or 'quartic' fourth order) modifies the shape of the pulse, resulting in modulation, and may even lead to the appearance of pre- or post-pulses [5-9].

Definition of Skew

In order to characterize quantitatively the shape of the pulse, it is worthwhile to introduce the skewness parameter, *S*. The simplest, self-explanatory definition of *S* is based on the ratio of the 'tail-width-half-max' (TWHM) and the 'head-width-half-max' (HWHM) of the laser intensity, as, for example, *S*=(TWHM/HWHM)-1. In addition to this heuristic definition of the skewness, a variety of more rigorous analytical expressions involving more features of the envelope function, *I(t)*, can be used. In the particular case of laser-plasma accelerators, the following definition of skew based on second and third order moments [10] proved to be useful:

$$S = m_3 \big/ m_2^{3/2}, \;\; m_k = \int_{t_a}^{t_b} (t - t_0)^k I(t)dt \Big/ \int_{t_a}^{t_b} I(t)dt \qquad (1)$$

In practical cases the limits of integration, t_a and t_b, can be set according to the meaningful amplitude level of the retrieved pulse shape just above the noise level of the measurement. S=0 corresponds to symmetric pulse shape, S<0 describes a pulse with a slowly increasing front part and suddenly dropping tail, while S>0 represents a fast increase and long tail.

Skew-flips

In a typical chirped pulse amplification (CPA) system, the final pulse-forming device is the grating pair pulse compressor. In contrast to the most simplistic view, by scanning the grating separation the experimenter changes not only the pulse length and the linear chirp, but also modifies all the higher order terms [7-9], and consequently the pulse shapes. The effects on the pulse shape become negligible at settings far from the shortest compression. On the other hand, when the pulse duration is in the range of a few times the minimum and the compressor angle is set slightly off from the optimum, or when the pulse contains not fully compensated higher-order terms, then a typical scan around the shortest pulse will produce significant changes to the pulse shape. For example, by compressing stretched pulses with a positive bias third-order phase component, the pulse shape in the course of a compressor separation scan initially will be skewed toward the head of the pulse (S>0), then flips to become a skewed pulse at the tail (S<0), and finally flips back again to the original asymmetric one (S>0) as the solid curve shows in Fig. 1a. It must be emphasized, that these changes of the pulse envelope are fundamentally different from the well-known and widely used mapping of the spectral amplitude to the time domain for strongly chirped pulses, where only the dominant, second-order phase coefficient plays any role [3].

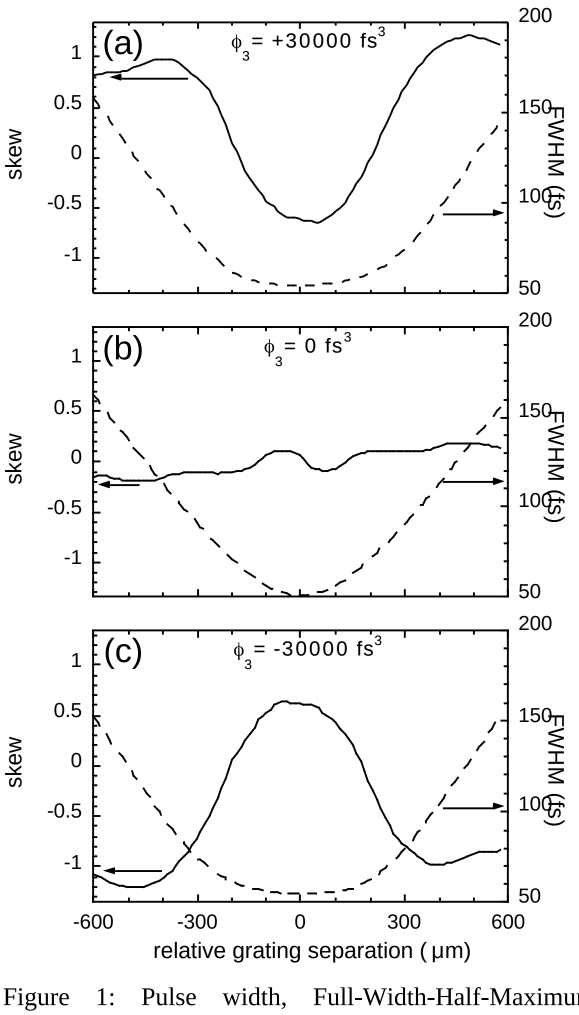

Figure 1: Pulse width, Full-Width-Half-Maximum, FWHM (dashed curve) and skew, S, (solid curve) of ultrashort pulses in a CPA system plotted around the best compression in the function of the grating separation for three cases of third order bias phase components

Further details of this ‘skew-flip’ behavior can be examined in the three panels of Fig. 1, which show the simulated pulse shape dependence for ~20 nm spectral bandwidth during a compressor scan around the shortest pulse for three specific third order bias values. The grating parameters are: groove density = 1480 mm^{-1}, angle of incidence = 50.0 deg, grating separation at the shortest pulse = 323 mm, and λ = 795 nm.

EXPERIMENTS

In a real laser system, however, the situation is complicated by the non-negligible presence of even higher order, generally uncompensated, phase terms beyond the third, associated again with the material dispersion in the components of the laser system. The solid curve in Fig. 2 shows the results of a full simulation of the pulse shape evolution in our Ti:sapphire CPA laser. The squares correspond to measured data, averaged for 5 laser shots. The pulses were fully characterized by retrieving the amplitude and phase functions from Polarization-Gate Frequency Resolved Optical Gating (PG-FROG) images [11,12]. The two inserts in Fig. 2 show example retrievals at the positive chirp side (a) and at the negative chirp side (b), respectively. While both pulses have the same FWHM pulse duration (76 fs), the pulse at the positive chirp side has sharper rising edge than the pulse with negative chirp – in good agreement with the simulation results and the skew definitions above.

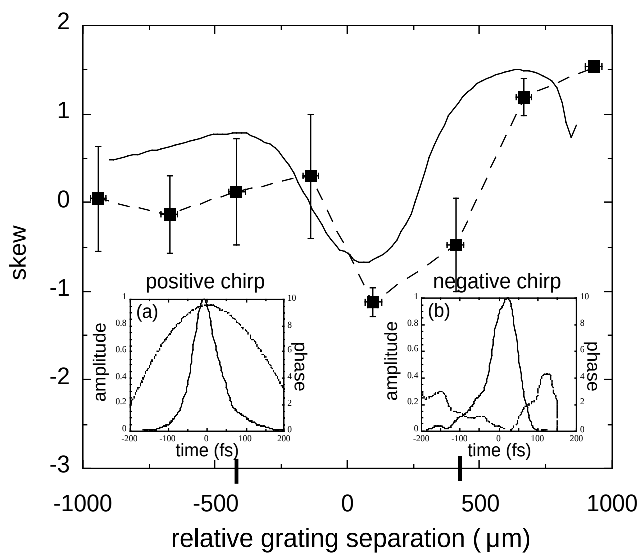

Figure 2: Simulated (solid curve) and measured (squares) skew of pulses in a CPA system around the best compression plotted in the function of the grating separation. Inserts show retrieved amplitude and phase functions in the time domain at the marked relative grating separations. (a): -420 μm, positive chirp side, (b): +410 μm, negative chirp side.

The modulations at the rising edge of the negatively chirped pulse indicate the presence of unbalanced third and higher order phase terms. These unbalanced terms are eventually responsible for the seemingly general 'chirp/shape' relationship of 'positive chirp = faster rise time and slower fall time; negative chirp = slower rise time and faster fall time' observed in our laser setup.

It should be noted, however, that for other experimental parameters (e.g., different mismatch of the stretcher/compressor or different stretcher/amplifier chain designs), balanced compression could manifests itself differently at 'off-shortest' pulse durations (off-shortest compressor settings), leading to different 'chirp/shape' combinations. The above analysis shows the possibility of laser pulse shape control by the simple method of grating alignment and change of separation without the insertion of sophisticated pulse shapers. For example, by decreasing the angle of incidence on the gratings by 0.6 degree, the effect of the added $\varphi_3 = +30000\ fs^3$ third order phase component makes possible to generate positively- or negatively-skewed pulses at different positions along the grating scan.

SELF-MODULATED LWFA

To illustrate the practical importance of the skewness of ultrashort laser pulses, we describe a strongly nonlinear experiment: the acceleration of electrons by laser produced plasma wakes in the SM-LWFA regime. In laser plasma acceleration experiments at the L'OASIS Lab of LBNL (Ti:sapphire CPA laser system, ~0.5 J compressed energy in >45 fs pulses, He gas target excited by ~$1.5\text{x}10^{19}$ W/cm^2 peak intensity), we observed strong asymmetry in the yield of electrons and neutrons produced by the accelerated electrons of multiple-tens of MeV energy as a function of the compressor scans [1,2]. The total charge of the emitted electrons has been found to depend strongly, and asymmetrically, on the position of the grating separation relative to the optimum pulse compression setting. Analytic modeling and simulation indicate that the effect of the intrinsic frequency chirp is less important and itself can not explain the observed anomaly [13]. On the other hand, taking into account the shape dependence, it is possible to explain the observed asymmetric enhancement; according to Raman instability analysis, faster rise times generate larger plasma wakes underneath the laser pulse envelope, resulting in larger plasma waves and eventually larger electron yield.

SUMMARY

In conclusion, we have shown that appropriate knowledge and control of the pulse shapes in grating-based CPA systems can be used for optimization of a laser wake-field accelerator. The interplay of pulse shapes, skewness, and sign of chirp can lead to an enhanced growth of the plasma wake responsible for electron acceleration. In the experiments, pulse shaping is achieved with a conventional grating compressor scan by intentionally offsetting the higher order phase components. This method of higher order phase control is a simple alternative to the recently developed acousto-optic phase modulation devices such as the DAZZLER [4,14], and can conveniently be used at arbitrarily high power and energy levels limited only by the damage threshold of the compressor gratings.

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