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On the temporal contrast of high intensity femtosecond laser pulses*

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Abstract

The temporal contrast is classified into two main regimes, the nanosecond-scale and the picosecond-scale contrast prior to the main pulse. The Lund terawatt laser system is shown to be improved on the nano- and picosecond-scale by a factor of 10 and 50, respectively, when it was optimized for contrast but not for energy. Calculations are also presented to emphasize the role of angular dispersion on the picosecond contrast. Finally we show a compromise between the duration and contrast of femtosecond laser pulses amplified in an optical parametric (chirped pulse) amplifier.

Keywords: High intensity lasers; Optical parametric amplification; Pulse compression; Temporal contrast

1. INTRODUCTION

In most of the recent and exciting applications of high power femtosecond laser systems, the temporal contrast of the laser pulses is a key parameter. When the intensity on solid targets of experiments like high harmonics generation from solids (Foldes *et al.*, 2003) or proton and ion acceleration (Shorokhov & Pukhov, 2004) from thin foils, falls in or beyond the 10^{17} W/cm^2 range, it is essential that the femtosecond laser pulses exhibit good temporal contrast. That is, in general the intensity of the electromagnetic field prior to the main laser pulse should be at least 5–8 orders of magnitude lower than that of the main pulse; otherwise the target may become evaporated by the time the main pulse arrives. Hence, it is practical to define the temporal contrast as the ratio of the intensity of the pedestal or sub-peak to the intensity of the main pulse.

It seems practical to divide the contrast problems into two parts. The first one can be called "nanosecond-scale" contrast which describes the situation well before the main pulse. The contrast degradation of this type is primarily given by the laser amplification technology and includes amplified spontaneous emission (ASE) and prepulses originating from non-complete suppression of the pulse train from the femtosecond oscillator as well as spurious reflections on various optical elements.

The other, maybe less trivial type of contrast degradation in chirped-pulse-amplification (CPA) laser systems, named as picosecond-scale or intrinsic contrast, can be observed as sub-peaks temporally close (1–10 ps) to the main pulse. It is uniquely defined by the spectrum and the spectral phase shift (chirp) of the pulse as well as by the angular dispersion of the laser beam.

Efforts aiming to improve any of the two contrast types almost certainly affect the other one. Hence, the improvement of a laser system requires several subsequent steps and often results in compromises as will be shown in the following sections.

In this paper, we first show how the temporal contrast of an existing 20-TW laser system can be improved by more than an order of magnitude without re-designing and re-building the system. In the next part, calculations are presented on contrast degradation due to residual angular dispersion of the laser system. Finally we analyze the ultimate contrast achievable from an optical parametric chirped pulse amplifier.

2. CONTRAST ENHANCEMENT USING CLASSICAL WAYS

The Lund multi-terawatt laser system is capable to serve two target areas simultaneously. One is the "Short pulse
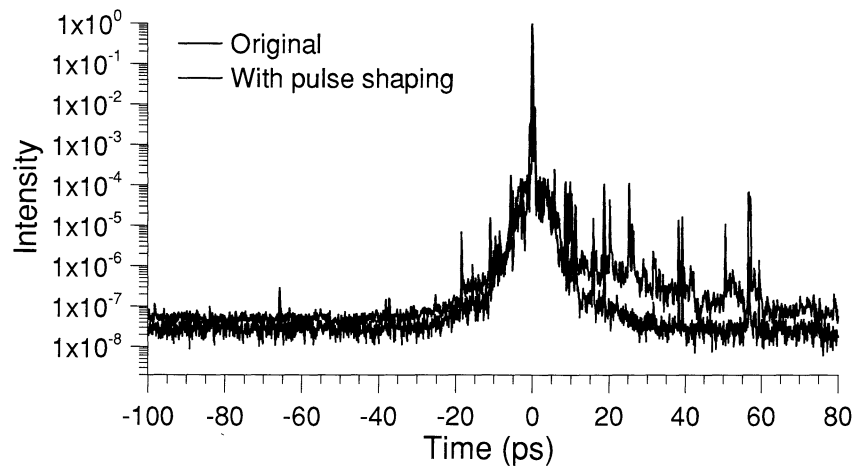

Fig. 1. Temporal contrast of the 20 TW laser with and without shaping the spectrum of the seed pulse.

target area" (SPTA), which is provided with about 80% energy of the beam amplified in a regent, and a 5 pass Ti:S amplifier, resulting in a compressed pulse of <50 fs and 130 mJ. The other one is the "Multi-terawatt target area" (MTTA), which is fed by the laser beam of 20% energy further amplified in a four pass Ti:S power amplifier, giving routinely 1 J, <50 fs pulses on the target, with focused intensity exceeding 10^{19} W/cm^2.

The temporal contrast is measured by a commercially available-third order cross correlator, Sequoia. Its factory settings offers a dynamic range of 10^8, which we further optimized up to 10^9.

One of the main bottlenecks of many CPA systems is the regenerative amplifier, since it has to exhibit stable amplification with large gain in excess of 10^6. These conditions result in gain narrowing and saturated amplification. The former sets a limit to the bandwidth of the amplified pulse while the latter enhances the level of ASE.

As it was first suggested by Backus *et al.* (1998), gain narrowing effect can be reduced by shaping of the pulse spectrum prior amplification. Installing an acousto-optical modulator, Dazzler (Verluise *et al.*, 2000), after the femto-second oscillator, we increased the bandwidth by more than 50% achieved. This led to an improvement of the nanosecond contrast by a factor of 2.5 (Fig. 1).

Further experiments were performed to study how the temporal contrast affected when the gain of the regenerative amplifier is changed. A good balance was found when the gain was reduced by a factor of 4, at which the amplification was still fairly stable but exhibited less saturation, and also less gain narrowing hence broader amplified spectra.

The temporal contrast was thus improved in several ways (Fig. 2). Since the amplified bandwidth was broader, the compressed peak pulse was shorter, and its intensity larger. The ASE background was less amplified due to the reduced level of saturation. These effects resulted in an improve-
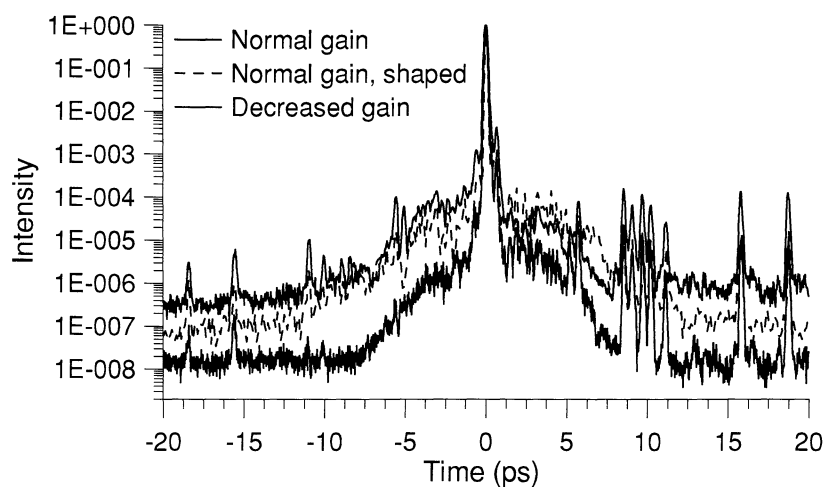

Fig. 2. Improved temporal contrast when the gain of the regenerative amplifier was reduced to its quarter.

ment on the nanosecond scale by larger than an order of magnitude, from 3×10^{-7} to 1.8×10^{-8} and by a factor of 50 on the picosecond scale, at the pedestal around the main peak.

By using a fast photodiode, the temporal structure well before the main pulse was also measured. Initially we found that the regenerative amplifier, due to the general construction principle and the limited extinction ratio of the polarization optics, significantly amplifies pulses before the main one from the pulse train of the 80 MHz repetition rate oscillator. By changing the delay of the pump pulse of all the amplifiers that is the regenerative amplifier and the two multiple-pass Ti:S amplifiers, we almost completely eliminated these prepulses (Fig. 3). In this case, the price of the good contrast was a trade-in of 10% loss in the total output energy.

These improvements allow us to establish a new mode of operation of the laser system for experiments requiring optimized pulse contrast. In the normal mode, with the two arms operating parallel, a beam-splitter is used to seed the final amplifier of the multi TW arm with only 20% of the pulse energy after the first multi-pass amplifier. In the high contrast mode, this beam-splitter is replaced with a mirror, and the gain of the regent reduced by a factor of 4. It allows improved contrast in the multi TW arm, but at the sacrifice of the other arm being idle.

As a good example, the Lund laser system became able to implement successful experiments on particle acceleration. Due to the high temporal contrast, we were able to accelerate protons to energies $\sim$5 MeV using thin (6 μm) Al target foils (Lindau *et al.*, 2005). Further improvement of contrast may require more sophisticated techniques as use of a plasma mirror (Doumy *et al.*, 2004) implementing a double-CPA system (Kalashnikov *et al.*, 2004, 2005) or frequency conversion (Uteza *et al.*, 2005).
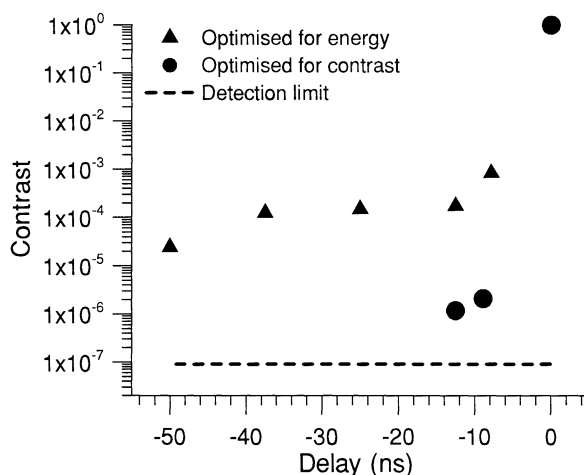

Fig. 3. The temporal structure of the laser system well before the main pulse when the laser is optimized for energy (triangles) and for contrast (dots).

3. DISPERSION AND TEMPORAL CONTRAST

As it is known, the uncompensated material dispersion of the laser system makes the high power pulse leaving the compressor chirped, means its phase is spectrally dependent. It is customary to describe the chirp with its Taylor series, where the second and third order derivatives of the spectral phase are the group delay dispersion (GDD) and third order dispersion (TOD), respectively. The former is responsible for the temporal lengthening of the pulse while the TOD redistributes the frequencies in time giving rise to side-peaks in the temporal domain (Fittinghoff *et al.*, 1998; Wang *et al.*, 1999). The intensity of these sub-peaks increases with TOD, hence the picosecond-scale temporal contrast is degraded (Osvay *et al.*, 2000).

A similar but maybe less obvious effect is caused by non-compensated angular dispersion, which makes the pulse temporally chirped and its pulse front tilted (Diels & Rudolph, 1996). It happens typically if the grating pairs in a stretcher or a compressor of a CPA laser are slightly misaligned or the pulse propagates through wedged optics (Osvay & Ross, 1994; Osvay *et al.*, 2005; Pretzler *et al.*, 2000). This residual angular dispersion, defined by the angle between the spectral phase fronts, not only lengthens the pulse due to the introduced group-delay dispersion (GDD) but also introduces uncompensated third-order dispersion (TOD) in the system (Osvay *et al.*, 2004).

Figure 4a shows the duration of a Gaussian pulse having a transform limited length of 10 fs in the function of angular dispersion for different lengths of propagation. One can see that even a small amount of angular dispersion of 2 μrad/nm lengthens the pulse duration by 20% on a target 10 m away.

Figure 4b displays the contrast degradation calculated from the spectra of 10 fs transform limited Gaussian and sech^2 pulses by Fourier transformation. Here only the TOD was assumed to be different from zero due to residual angular dispersion. As can be seen, the contrast cannot be expected to exceed 10^{-7} if the residual angular dispersion is as modest as 2 μrad/nm. For comparison, this value is not very far from the usual precision of the currently available techniques (Dorrer *et al.*, 2002; Varjú *et al.*, 2002; Akturk *et al.*, 2003), and can be caused by 2.5 mrad non-parallelism of a 1200 mm^{-1} grating pair compressor.

Please note that unlike to the non-compensated material dispersion, the GDD and TOD due to angular dispersion are increasing with the distance from the angular disperser (Osvay *et al.*, 2004). Hence, it would be possible to fully compensate for it only at a given distance by applying opposite sign material dispersion. In large laser systems the compressor is usually aligned with monitoring the pulse length and chirp only. Without measuring the angular dispersion in the beam, this procedure would result in almost transform limited pulses with good contrast only on targets which positioned at the same distance from the laser as the pulse measuring device.
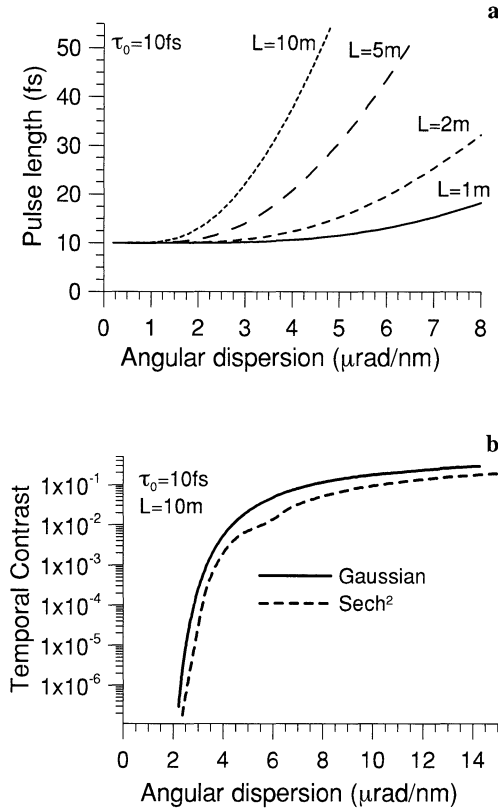
Fig. 4. Temporal broadening (a) and contrast degradation (b) of a transform limited 10 fs pulse in the function of angular dispersion after propagating L distance from the angular disperser.

4. OPTICAL PARAMETRIC CHIRPED PULSE AMPLIFICATION

One of the recent major developments in the technology of high intensity laser system is non-collinearly phase-matched optical parametric chirped pulse amplification (OPCPA), first mentioned by Dubietis et al. (1992). It offers broad bandwidth with almost no gain narrowing, amplifies only one pulse from the pulse train and usually exhibits lower level parametric fluorescence than the ASE level of Ti:S amplifiers (Ivanov et al., 2003; Yoshida et al., 2003). Hence, OPCPA has started being widely used not only as a preamplifier in high power lasers (Collier et al., 1999; Jovanovic et al., 2002) but there are also examples for "OPCPA only" systems (Ross et al., 2000; Yang et al., 2002).

The enthusiasm of using OPCPA for amplification of 10 fs and even shorter 800 nm pulses, supported by the extremely broad spectral gain, has to face a compromise in temporal contrast. Namely, although the spectral gain calculated in the most optimistic way (Ross et al., 1997) is indeed very broad but it exhibits a sharp cut in the shorter-wavelength side (Fig. 5). Since the spectrum of a short pulse ultimately determines its temporal shape via Fourier transform, sharp spectral cuts always result in distorted temporal contrast (Osvay et al., 2000; Collier et al., 2001). Hence, the
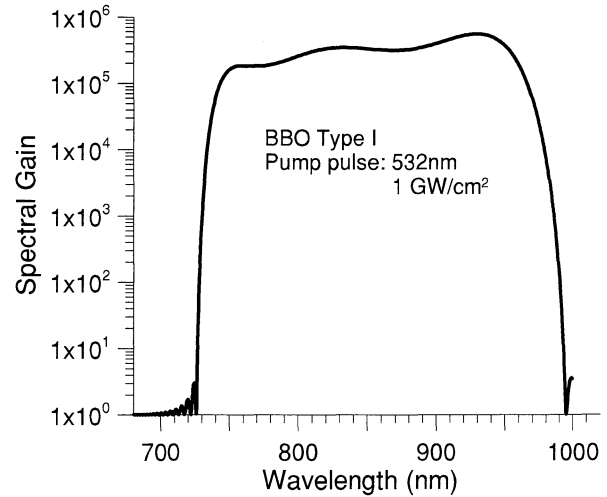

Fig. 5. Spectral gain of a non-collinear optical parametric amplifier at 800 nm. Note the sharp cut of the spectrum even on the logarithmic scale!

shorter the pulse is the higher intensity level of the amplified spectra gets distorted at. Consequently, the picosecond-scale temporal contrast of the shorter pulses would be heavily degraded exhibiting not only sub-peaks but also a broader pedestal (Fig. 6). Hence, we can establish the compromise between pulse duration and contrast as follows. The optical parametric amplification of 10 fs, 20 fs, and 25 fs pulses results in a picosecond-scale temporal contrast of 3.3×10^{-4}, 1×10^{-8}, and 6×10^{-11}, respectively.

One solution for this problem may be if one broadens further the bandwidth of spectral gain using sophisticated techniques. The one based on the use of more pump beams at different angles (Zeromskis et al., 2002; Wang et al., 2004) seems rather promising, while others applying angularly dispersed beams (Arisholm et al., 2004; Cardoso &
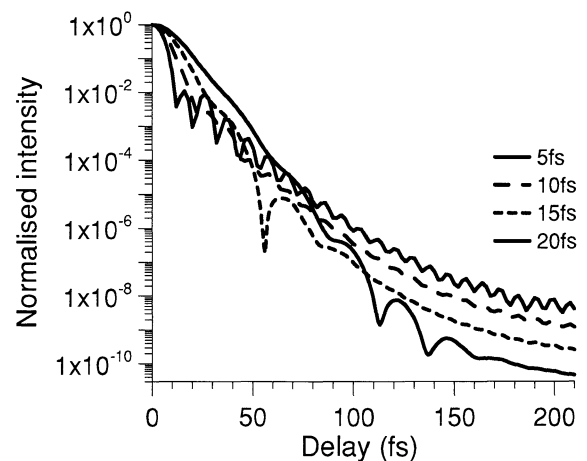

Fig. 6. Temporal shape of Gaussian laser pulses following the amplification in an OPCPA system.

Figueira, 2004) need more attention due to the contrast problems of non-compensated angular dispersion discussed above.

5. CONCLUSION

In our paper, we proved experimentally that an optimization of a CPA laser system for contrast instead of output energy may result in more orders of magnitude improvement of temporal contrast with a trade in of only 20% reduction of output energy. Then we presented the results of our calculation on the deterioration of pulse contrast due to uncompensated higher-order angular dispersion arising, that is, from the misalignment of the stretcher-compressor system of a CPA laser. Finally we showed that the optical parametric chirped pulse amplification of 800 nm pulses with duration of 20 fs and 25 fs there is a compromise between the duration and contrast of femtosecond laser pulses obtained from optical parametric chirped pulse amplification (OPCPA) system.

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