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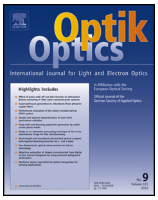

Temporal contrast improvement in chirped pulse amplification systems by a four-grating compressor and by spectral modifications

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ABSTRACT

The quest for higher peak focused intensities and better temporal contrast drives one to improve the design of all possible stages of the chirped pulse amplification (CPA) system. In this paper, we have analyzed the role of dispersion and spectral profile on the temporal shape and contrast ratio of the output pulse of a CPA system. The simulations indicate that an initial sech^2 or a Gaussian pulse in the CPA system is best for a good contrast ratio. Incorporating a four-grating based pulse compressor in the CPA system improves the contrast as well as provides the flexibility to compensate the dispersion upto the fourth order. The simulations also detail the effect of spectral profile tailoring on the contrast ratio and peak power.

1. Introduction

Temporal pulse contrast is a very important parameter in high-intensity laser plasma physics experiments where poor temporal contrast caused by pre-pulses and background pedestals can change the properties of targets [1,2] before the arrival of the main laser pulse. Many of the laser systems built using the chirped pulse amplification (CPA) technology reach peak focused intensities that exceed 10^{21} W/cm^2 [3,4]. But with the presence of a pedestal and pre-pulses, intensity levels in the range of 10^{11}–10^{12} W/cm^2 can bring about the formation of plasma before the arrival of the main pulse. Thus, making a clean and pre-plasma free laser matter interaction impossible. The key requirement is the method of generating pulses having high temporal contrast. An appropriate knowledge of the parameters that can manipulate the pulse shapes in CPA systems can help for optimization of the entire system. Though the operation of a chirped pulse amplification system (CPA) is largely well understood, the improvement in such a system is still an ongoing process.

Generally, temporal contrast is defined as the ratio of the intensity of the main pulse to the intensity of the pedestal or sub-peak pulse. The contrast can be classified into two main regimes, the nanosecond scale and the picoseconds scale contrast prior to the main pulse. The nanosecond scale contrast describes a situation well before the main pulse and it is mainly due to the amplified spontaneous emission (ASE) and pre-pulses originating in the pre-amplifier stage like the regenerative amplifier or the multipass amplifier. Several methods have been developed to remove the ASE, like cross-polarization wave generation in nonlinear crystals [5], saturable absorber techniques [6], and the plasma mirror method [7]. The optical parametric chirped pulse amplifier (OPCPA) was proposed as a low ASE pre-amplifier [8], and the double chirped pulse amplifier lasers have been shown to give a temporal contrast of 10^{10} [9] and a double OPCPA can show a contrast greater than 10^{10} [10] .The characterization of pulse contrast must consider not only ASE but also temporal shape irregularities like extended wings of the main pulse itself. This is quantified by the picoseconds scale contrast (observed temporally closer to the main pulse) and it is defined by the spectrum, chirp of the pulse, the angular dispersion, and phase aberrations. As pulses propagate in a CPA system, they undergo phase distortions [11] due to the dispersion (produced by optical elements in the system) and it strongly depends on the duration and bandwidth of the pulse. In real CPA systems the non-negligible higher order phase terms associated with the material dispersion in the components of the laser system limits the fidelity of recompression [12]. The CPA laser systems require higher order dispersion control in stretching, amplification, and recompression. In this paper, we have analyzed the optical design of the compressor and the spectral shaping of the propagating pulse. Incorporating these design parameters in the architecture of the total CPA system, achieves high contrast in the final recompressed pulse.

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2. Basic formulation

The output of any ultra fast optical system has been determined by the phenomenon of dispersion. The development of ways to characterize or manipulate dispersion in the total system has led to shorter and high fidelity optical pulses. Propagation in any dispersive medium generally starts with the description of the input pulse as the field $E(t)$ at time t and having a central frequency ω_0. To find the output pulse one has to calculate the Fourier transform of $E(t)$.

$$g(\omega) = \int_{-\infty}^{\infty} E(t)e^{i\omega t}\mathrm{dt} \tag{1}$$

and then multiply by $\exp(i\phi(\omega))$ where $\phi(\omega)$ is the phase shift through the system .

$$G(\omega) = g(\omega)e^{i\phi(\omega)} \tag{2}$$

At this stage depending on the optical system, the phase shift $\phi(\omega)$ can be incorporated and the spectral profile $g(\omega)$ too can be modified . Now taking the inverse Fourier transform one obtains the output field *E(t')* and therefore the output pulse,

$$E(t') = \frac{1}{2\pi}\int_{-\infty}^{\infty} G(\omega)e^{-it'\omega}d\omega \tag{3}$$

Propagation through a dispersive device like stretcher or compressor or material introduces a frequency dependent phase shift that is expressed as a Taylor expansion [13] about the central frequency ω_0.

$$\phi(\omega) = \sum_{n}\frac{1}{n!}\phi^{(n)}(\omega_0)(\omega-\omega_0)^n \tag{4}$$

Here $\phi^{(n)}(\omega_0)$ is the nth derivative of the phase function with respect to frequency, evaluated at ω_0 with unit of fs^n. The dispersive properties of the elements of the system are given by the coefficients $\phi^{(n)}(\omega_0)$ [14]. The second order derivative of the spectral phase function $\phi^{(2)}$ is the group delay dispersion (GDD) and the third order derivative of the spectral phase function $\phi^{(3)}$ is the third order dispersion (TOD). GDD is responsible for the lengthening of the pulse and TOD gives rise to the side peaks or wings in the temporal domain. $\phi^{(4)}$ is the fourth order (FOD), or quartic dispersion, $\phi^{(5)}$ is the fifth order or quintic dispersion (QOD) and so on. In the CPA system, for reasonable recompressed final pulse, the second order dispersion and the third order dispersion of the stretcher/compressor and the amplifying medium needs to be controlled such that

$$\begin{gathered}\phi^{(2)}_{(\mathrm{stretcher})} + \phi^{(2)}_{(\mathrm{material})} + \phi^{(2)}_{(\mathrm{compressor})} = 0;\\ \phi^{(3)}_{(\mathrm{stretcher})} + \phi^{(3)}_{(\mathrm{material})} + \phi^{(3)}_{(\mathrm{compressor})} = 0\end{gathered} \tag{5}$$

The difficult problem of pulse compression of large bandwidth signals is the uncompensated cubic phase distortion or the third order dispersion (TOD). A 10 fs wide initial pulse after undergoing the process of stretching, amplification, and recompression will have an asymmetric tail in the range of 100 fs due to residual TOD only. This means an effect on the contrast ratio. Fig. 1 depicts the simulation of the contrast ratios (in the 100 fs range) due to TOD in case of three initial temporal profiles. One is a sech^2 initial pulse and the other two pulse shapes can be described as $\exp(-(t/\tau)^{2N}/2)$ where τ is the half pulse width at e^{-1} intensity.

It can be a Gaussian initial pulse ($N = 1$) or a super Gaussian initial pulse ($N > 1$). The super Gaussian ($N = 2$) input pulse was considered for a mildly flat topped temporal profile. An oscillator producing a short pulse will have a sech^2 profile while a Gaussian profile occurs after expansion in a grating based stretcher. The super Gaussian may be obtained in an optical fiber based stretcher, where the pulse is chirped into a long pulse due to self phase modulation and group velocity dispersion. Fig. 1 shows that a sech^2 pulse after recompression has a slightly better contrast ratio than an initial Gaussian pulse, but in order to achieve contrast ratio $>10^5$, for both type of temporal profile, the TOD in the system should not be greater than 100 fs^3. For a TOD tending to 0 fs^3 obviously the contrast ratio is very large (Fig. 1) because the tail would be absent in the final output pulse.

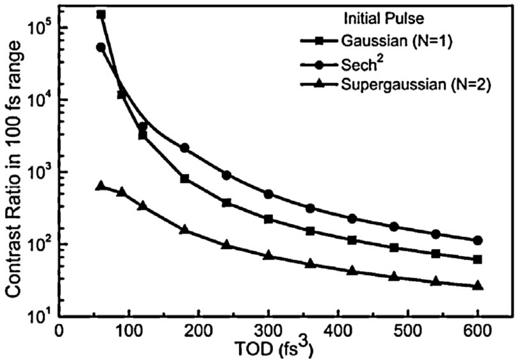

Fig. 1. Contrast ratio of the final recompressed pulse due to TOD in a CPA system. Three initial pulses considered are Sech^2, Gaussian, and super-Gaussian.

Zeroing the GDD and the TOD may not always work well for many real systems. Sometimes best results [15] are obtained not just by cancelling $\phi^{(2)}$,$\phi^{(3)}$, and $\phi^{(4)}$but by finding the best trade-off between these terms. Following the Eqs. (1)–(4), we simulated the final pulse shape when FOD has been introduced into the system along with TOD during the passage of the pulse through a CPA system. For a 10 fs initial Gaussian temporal profiled pulse, the TOD of 600 fs^3 results in a contrast ratio of 61. Including a FOD of 9600 fs^4 with TOD of 600 fs^3 widens the pulse width from 10 to 13.65 fs and marginally decreases the contrast ratio to 53, and the tail or the pedestal reduces. If one includes a fifth order dispersion of 78,000 fs^5 with a TOD dispersion of 600 fs^3, the contrast ratio improves by an order of magnitude from 61 to 787 and the altered pulse shape has a low pedestal. Pulse shape changes leads to significant difference in the interaction with plasmas, for example, in laser wake field acceleration [16]. Also by reducing the pedestal or wings of the pulse one ensures that the energy extracted in the amplification process remains in the main pulse only and the pedestal contains minimal energy.

3. Stretcher and compressor optimization

The stretcher and the compressor introduce dispersion into the CPA system and they can also be used to manipulate uncompensated dispersion in the system. Stretched and chirped pulses in many CPA systems are obtained by use of single mode fiber, while gratings are used in many other systems to obtain stretching and chirping. Since self phase modulation in fibers tend to result in a slightly flat topped pulse profile, which further results in low contrast ratio (Fig. 1), it is best to choose grating pair based stretchers [17,18]. A Martinez type stretcher [17] can generate positive GDD and a Treacy type [14] grating pair compressor generates negative GDD and if the stretcher and compressor are rigorously complementary, then there is no temporal effect on the recompressed pulse, because all orders of dispersion would have been compensated. Maintaining the perfect alignment of the gratings in the stretcher and compressor is not a trivial task in a large CPA