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The influence of output pulse spectral shape and bandwidth on pulse contrast in the chirped pulse amplification

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ABSTRACT

A simple model is presented to analyze the spectral shape and bandwidth dependence of the pulse contrast and compressed pulse width in the chirped pulse amplification. The parameters of the 30 fs laser system are demonstrated as examples. Comparing with Top hat, Lorentzian, Sech^2, Gaussian, 2nd Super Gaussian and 10th Super Gaussian spectral pulse shape, the 2nd Super Gaussian spectral pulse shape can obtain better contrast in the case of less spectral bottom width. Those results are helpful to find an optimized spectral shape in the chirped pulse amplification.

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1. Introduction

In the chirped pulse amplification (CPA) laser system [1], the temporal contrast between the main pulse and prepulses is an important factor [2]. The peak laser intensity up to 10^{22} W/cm^2 is now achievable and is expected to boost to 10^{24} W/cm^2 in the near future [3]. However, in the application of a high-intensity laser to solid-target experiments, the 10^{10} W/cm^2 prepulse is strong enough to generate unwanted plasmas before the main pulse arrives on the target and modify the target conditions [2]. So it is important to develop higher temporal contrast in CPA laser system.

There are many temporal contrast-limiting factors [4–11], such as spectral shape and bandwidth, amplification of spontaneous emission (ASE), residual high-order dispersion and spectral phase distortion. Among these factors, the spectral shape and bandwidth, not only affect the temporal contrast, but also affect the final compressed pulse width, is very important. In the previous literature, the calculation of the pulse contrast is generally assumed that the spectral shape of the output pulse is Gaussian pulse. Therefore, the conclusions on the pulse contrast are generally based on the Gaussian pulse. However, with the development of the optical parametric amplification (OPA) technology, the spectral shape of the output pulse may be super Gaussian or other complex shapes. In this case, the conclusions about pulse contrast based on the Gaussian pulse are no longer correct.

In this article, we focus on the temporal contrast affected by the spectral shape and bandwidth in CPA lasers. As an example, we analyze the impact of the Lorentzian, Sech^2, Gaussian, 2nd Super Gaussian, 10th Super Gaussian and Top hat spectral pulse shape on the temporal contrast. And we special emphasis on the description of the spectral full bandwidth at half maximum (FWHM) and the spectral bottom width, which is often not very clear in the past literature.

2. Model

The pulse contrast is associated with the temporal distribution of the normalized laser intensity. The final output pulse contrast can be given by

$$I(t) = \left| \int_{\lambda_1}^{\lambda_2} A_{\text{output}}(\lambda) \exp\left[-i\frac{2\pi c}{\lambda} t + i\phi(\lambda) \right] \left(\frac{c}{\lambda^2} \right) d\lambda \right|^2, \tag{1}$$

where λ_1 and λ_2 are the minimum and the maximum values of λ determined by the laser system ($\lambda_2 - \lambda_1$ is the spectral bottom

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width), and c is the speed of light in vacuum, $A_{\text{output}}(\lambda)$ is the pulse spectral function out of the compressor, $\phi(\lambda)$ is the residual dispersion of the laser system.

3. Numerical results

To demonstrate the temporal contrast affected by the spectral shape and bandwidth in CPA lasers, we take one 30 fs compressed pulse laser system as examples. The central wavelength is $\lambda_0 = 808$ nm, while the minimum and the maximum values are $\lambda_1 = \lambda_0 - b/2$ and $\lambda_2 = \lambda_0 + b/2$, b is the spectral bottom width. For simplicity, we neglect the influence of the residual high order dispersion, i.e., $\phi(\lambda) = 0$. Moreover, the pulse spectral functions out of the compressor are assumed to be expressed with the Lorentzian function, Sech^2 function, Gaussian function, 2nd Super-Gaussian function, 10th Super-Gaussian function and Top hat function respectively. Then the output pulse spectral functions can be written as follows:

Lorentzian spectral function:

$$A_{\text{output}}(\lambda) = \left[1 + 4(\sqrt{2} - 1)\frac{(\lambda - \lambda_0)^2}{\Delta\lambda}\right]^{-1} \tag{2}$$

Sech^2 spectral function:

$$A_{\text{output}}(\lambda) = \text{Sech}\left[\frac{2\ \ln(1 + \sqrt{2})(\lambda - \lambda_0)}{\Delta\lambda}\right] \tag{3}$$

Gaussian spectral function:

$$A_{\text{output}}(\lambda) = \exp\left[\frac{-2\ \ln 2(\lambda - \lambda_0)^2}{(\Delta\lambda)^2}\right] \tag{4}$$

2nd-order Super-Gaussian spectral function:

$$A_{\text{output}}(\lambda) = \exp\left[\frac{-8\ \ln 2(\lambda - \lambda_0)^4}{(\Delta\lambda)^4}\right] \tag{5}$$

10th-order Super-Gaussian spectral function:

$$A_{\text{output}}(\lambda) = \exp\left[\frac{-2^{19}\ln\ 2(\lambda - \lambda_0)^{20}}{(\Delta\lambda)^{20}}\right] \tag{6}$$

Top hat spectral function:

$$A_{\text{output}}(\lambda) = \text{rectpuls}\left(\frac{\lambda - \lambda_0}{\Delta\lambda}\right) \tag{7}$$

where $\lambda_0 = 808$ nm and $\Delta\lambda$ is the pulse spectral FWHM, which is determined by the final compressed pulse temporal FWHM.

The final compressed pulse temporal FWHM and the spectral FWHM are linked by the following expression in the case of meeting the Fourier-transform limit:

$$\Delta t \Delta\lambda \left(\frac{c}{\lambda_0^2}\right) = \text{TBP} \tag{8}$$

where Δt is the final compressed pulse temporal FWHM and TBP is the time bandwidth product.

In the case of achieving the same Fourier-transform limit compressed pulse, the spectral FWHM of the different spectral shape is different, as indicated in Eqs. (2)–(8). For example, Fig. 1 plot the spectral curves of the Lorentzian, Sech^2, Gaussian, 2nd Super-Gaussian, 10th Super-Gaussian, Top hat spectral shape in the case of 30 fs Fourier-transform limit compressed pulse. And the concrete required spectral FWHM of the above spectral shape is shown in Table 1. As shown in Fig. 1, with the same 30 fs Fourier-transform limit compressed pulse, the required spectral FWHM of the Lorentzian spectral function is the shortest (i.e. 10.3 nm), while the required spectral FWHM of the Top hat spectral function is the largest (i.e. 64.3 nm).

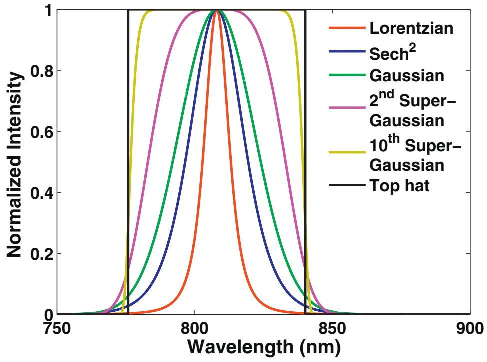

Fig. 1. Different spectral curves of the Lorentzian, Sech^2, Gaussian, 2nd Super-Gaussian, 10th Super-Gaussian, Top hat spectral shape in the case of 30 fs Fourier-transform limit compressed pulse.

Table 1
The required spectral bandwidth in the case of 30 fs compressed pulse, 10^{-10} pulse contrast.

Input spectral function	TBP	Δt (fs)	Required bandwidth (nm)	
			$\Delta\lambda$	$\lambda_2 - \lambda_1$
Lorentzian	0.142	30	10.3	>128
Sech^2	0.315	30	22.9	>128
Gaussian	0.441	30	32	>128
2nd-order Super-Gaussian	0.686	30	49.8	>90
10th-order Super-Gaussian	0.861	30	62.5	>70
Top hat	0.886	30	64.3	–

However, for a compressed chirped pulse, not only needs to consider the compressed pulse temporal width, but also needs to consider the pulse contrast. For the given spectral function, the spectral FWHM and the spectral bottom width determine the temporal width and contrast of the compressed pulse respectively. That is, for the given compressed pulse (for example, 30 fs), one needs to consider both the spectral FWHM and the spectral bottom width of the given spectral function. The temporal distribution of the normalized laser intensity corresponding to different spectral function curves in the case of the same 30 fs compressed pulse and the same 128 nm bottom width is plotted in Fig. 2. The 128 nm spectral bottom width is equal to 4 times spectral FWHM of the Gaussian function. It is seen that the temporal pulse contrast of the 2nd Super Gaussian spectral function is the best and reach to 10^{-20}, yet the temporal pulse contrast of the Top hat spectral function is the worst and only to 10^{-8}. Therefore, in order to achieve the same compressed pulse and the same pulse contrast,

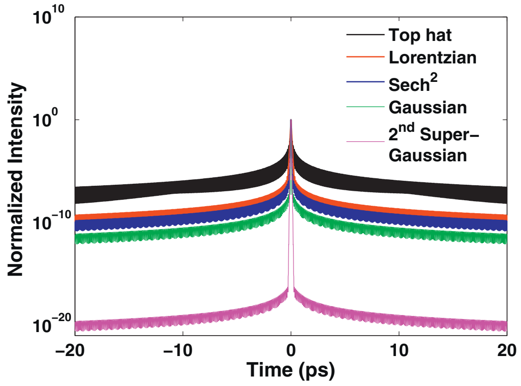

Fig. 2. The temporal distribution of the normalized laser intensity corresponding to different spectral function curves in the case of the same 30 fs compressed pulse and the same 128 nm spectral bottom width, including Lorentzian, Sech^2, Gaussian, 2nd Super-Gaussian, Top hat spectral function.

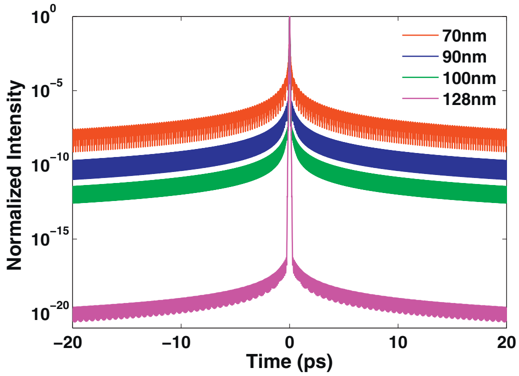

Fig. 3. The temporal distribution of the normalized laser intensity corresponding to different spectral bottom width in the case of the 30 fs compressed pulse and the 2nd Super-Gaussian spectral function.

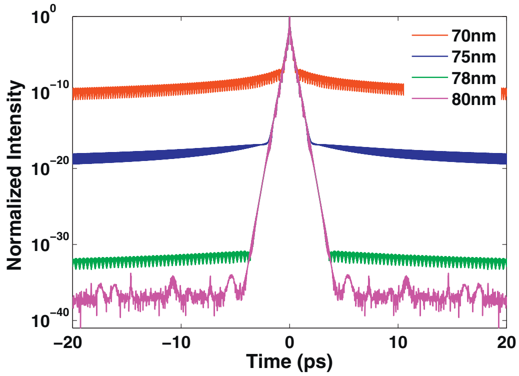

Fig. 4. The temporal distribution of the normalized laser intensity corresponding to different spectral bottom bandwidth in the case of the 30 fs compressed pulse and the 10th Super-Gaussian spectral function.

the required spectral FWHM and bottom width are different in case of the different of spectral function.

Further analysis showed that, when the spectral function is the Top hat function, the pulse contrast cannot achieve 10^{-10} no matter what spectral bottom width remains. For the Lorentzian, Sech^2 and Gaussian spectral function, the pulse contrast can achieve 10^{-10} when the spectral bottom width remains 4 times spectral FWHM of the Gaussian function. For the 2nd Super-Gaussian spectral function, the pulse contrast can achieve 10^{-10} when the spectral bottom width only remains 100 nm spectral width (equal to 3.1 times spectral FWHM of the Gaussian function), which is shown in Fig. 3. However, for the 10th Super-Gaussian spectral function, the pulse contrast can achieve 10^{-10} when the spectral bottom width only remains 70 nm spectral width (equal to 2.2 times spectral FWHM of the Gaussian function), which is shown in Fig. 4. Although the required spectral bottom width is very low for 10th Super-Gaussian spectral function, but the pulse contrast have been decreased in the case of few picoseconds.

4. Conclusion

In summary a simple model is presented to analyze the spectral shape and bandwidth dependence of the pulse contrast in the chirped pulse amplification. The parameters of the 30 fs compressed pulse laser system are demonstrated as examples. Comparing with the Top hat, Lorentzian, Sech^2, Gaussian, 2nd Super Gaussian and 10th Super Gaussian spectral pulse shape, the 2nd Super Gaussian spectral pulse shape can obtain better contrast in the case of less spectral bottom width.

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