Influence of spectral clipping in chirped pulse amplification laser system on pulse temporal profile

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ABSTRACT

Spectral clipping effect in a chirped pulse amplification laser system is developed in this paper. A grating-size-limited stretcher/compressor as well as an amplifier can alter the spectrum profile of an ultrashort pulse, so the temporal profile will be influenced. We present a model of spectral clipping effect and calculate the wavelength-dependent spectral clipping ratios in a CPA laser system for a variety of matched stretcher-compressor designs. Then we analyze the output pulse's temporal distribution, and find that the temporal contrast ratio is mainly determined by the stretcher and the amplifier. The pulse duration of the output pulse is mainly influenced by the amplifier.

Keywords: Chirped pulse amplification, spectral clipping, pulse compression

1. INTRODUCTION

Chirped pulse amplification (CPA) [1] is a key technique to achieve petawatt peak power [2] and intensity above 10^{20} W/cm^2, allowing for fast ignition [3] to be reached in future. The principle of CPA is not complex: stretching an ultrashort pulse in time, amplifying it and recompressing it prior to its original duration. The stretcher typically consists of a pair of gratings design with a negative separation that introduces a positive frequency chirp [4]. The compressor grating geometry must be matched to the stretcher to properly eliminate dispersion and thereby remove the chirp. The spectral clipping and the higher-order phase distortion in a CPA system are two important factors that significantly affect the fidelity of the output pulse. The spectral clipping caused by a grating pair compressor has been analyzed in a 400-fs CPA system [5], where the higher-order phase dispersion is negligible. The influences of the spectral clipping and the higher-order phase distortion in a matched stretcher-compressor design on the temporal distribution of the recompressed pulse have been investigated in a sub-100-fs CPA system [6]. The higher-order phase distortion in a 500-fs CPA system is negligible. However, the spectral clipping is still important which occurs in every part of the system, such as the stretcher, the amplifier and the compressor, due to the finite size of the optics (the gain narrowing [7] and the gain saturation [8] in the amplifier can be treated as a kind of spectral clipping effect). The spectral clippings in different parts of the system have different influences on the output pulse, which up to now have not been investigated in detail. This paper is devoted to a discussion on the spectral clipping effect in a chirped pulse amplification laser system and proposes a model. All of the influences of the spectral clippings caused by the stretcher, the amplifier and the compressor on the output pulse are a taken into account.

2. MODEL

The schematic of the parallel grating pair compressor [9] geometry is shown in Fig.1, and the perpendicular distance between the two gratings is G. The input chirped pulse laser beam has a top-hat spatial profile with a diameter ϕ and an

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incident angle γ. Because of the diffraction at the first grating the beam will be clipped by the second grating. Some wavelengths can pass the compressor without being clipped, some can partly pass the compressor, and the others cannot pass the compressor. As is illustrated in Fig. 1, the wavelengths form λ_1 to λ_2 can pass the compressor without being clipped. λ_1 and λ_2 ($\lambda_1 > \lambda_2$) are the critical wavelengths being clipped on each side of the second grating, whose first-order diffracted angles at the first grating are φ_1 and φ_2 respectively. And we define $\delta\lambda_c = \lambda_1 - \lambda_2$ as the bandwidth of the compressor. A certain wavelength λ, whose first-order diffracted angle at the first grating is $\varphi(\lambda)$, would be clipped by the second grating, and the clipped aperture $b(\lambda)$ at the vertical section of the beam, which is perpendicular to the grating grooves, is given by

$$b(\lambda)=\begin{cases}\left(\tan\varphi(\lambda)-\tan\varphi_1\right)G\cos\gamma & \left(\tan\varphi(\lambda)-\tan\varphi_1\right)G\cos\gamma\le\phi\\ \phi & \left(\tan\varphi(\lambda)-\tan\varphi_1\right)G\cos\gamma>\phi\end{cases}$$

$$\text{for } \lambda>\lambda_1, \tag{1a}$$

$$b(\lambda)=\begin{cases}\left(\tan\varphi_2-\tan\varphi(\lambda)\right)G\cos\gamma & \left(\tan\varphi_2-\tan\varphi(\lambda)\right)G\cos\gamma\le\phi\\ \phi & \left(\tan\varphi_2-\tan\varphi(\lambda)\right)G\cos\gamma>\phi\end{cases}$$

$$\text{for } \lambda<\lambda_2, \tag{1b}$$

$$b(\lambda)=0$$

$$\text{for } \lambda_2\le\lambda\le\lambda_1. \tag{1c}$$

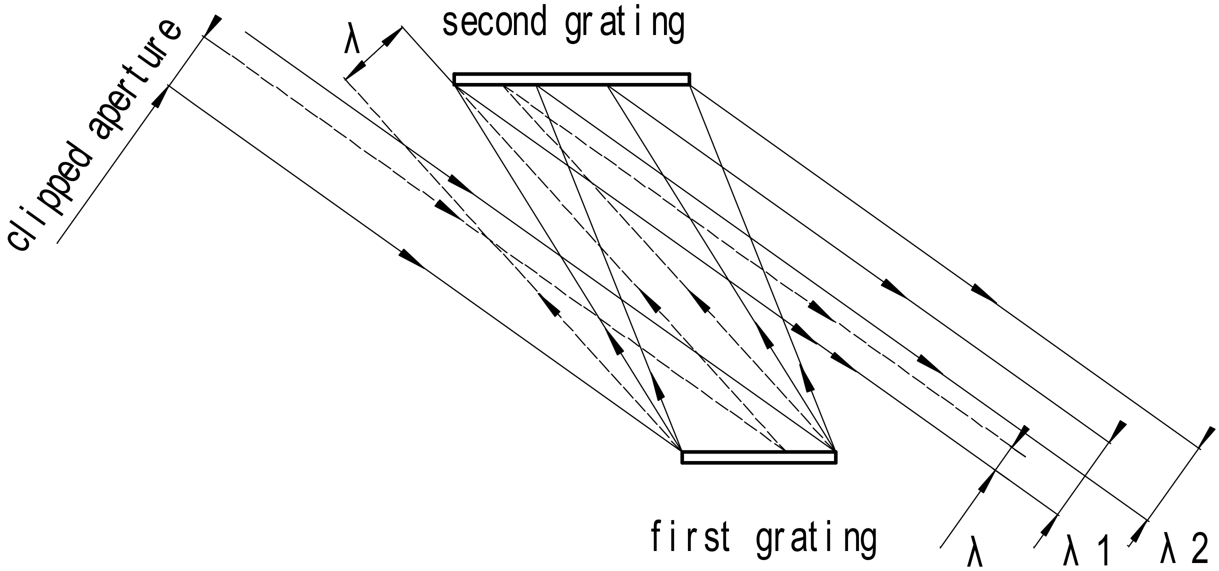


Fig. 1. Schematic diagram of a parallel grating pair compressor design, showing the wavelength-dependent spectral clipping at the second grating and the clipped aperture at the vertical section of the beam

According to the clipped aperture $b(\lambda)$, the wavelength-dependent clipping ratio of energy at the compressor $k_c(\lambda)$ can be obtained easily as

$$k_c(\lambda)=1-\frac{\alpha}{\pi}+\frac{\cos\alpha\sin\alpha}{\pi}, \tag{2}$$

with

$$\cos\alpha = \frac{\phi/2 - b(\lambda)}{\phi/2}. \tag{3}$$

An aberration-free stretcher can be treated as a grating pair design with a negative separation, which has a similar spectral clipping effect as analyzed above. But the diameter of the laser beam at the stretcher is significantly small and no wavelengths partly pass the stretcher. So the profile of the wavelength-dependent clipping ratio of energy at the stretcher $k_s(\lambda)$ has two rectangular edges, so that

$$k_s(\lambda) = \begin{cases} 1 & \lambda_4 \le \lambda \le \lambda_3 \\ 0 & \lambda > \lambda_3,\ \lambda < \lambda_4 \end{cases}, \tag{4}$$

where λ_3 and λ_4 ($\lambda_3 > \lambda_4$) are the critical wavelengths being clipped at the stretcher. Likewise, we can get the bandwidth of the stretcher $\delta\lambda_s = \lambda_3 - \lambda_4$.

At the amplifier, because of the gain narrowing and gain saturation, the spectrum profile and FWHM would be changed. We can use a wavelength-dependent function $k_A(\lambda)$ to describe this change. Therefore, in this CPA laser system, the intensity spectral profile of the output pulse $I_{output}(\lambda)$ is then

$$I_{output}(\lambda) = I_{input}(\lambda) k_s(\lambda) k_A(\lambda) k_c(\lambda), \tag{5}$$

where $I_{input}(\lambda)$ is the intensity spectral profile of the input pulse. Eq. (5) indicates that the output spectrum as well as some important parameters would be influenced by the stretcher, the amplifier and the compressor. For the temporal distribution, the intensity profile of the recompressed pulse is given by the inverse Fourier transform

$$I_{output}(t) = \left| FT^{-1}\left[E_{output}(\lambda) \right] \right|^2, \tag{6}$$

with

$$E_{output}(\lambda) = \sqrt{I_{output}(\lambda)}, \tag{7}$$

where $I_{output}(\lambda)$ is the intensity spectral profile of the output pulse given in Eq. (5).

3. CALCULATION AND RESULTS

Our CPA laser system consists of an aberration-free stretcher, an amplifier, a double pass grating pair compressor and an off-axis paraboloidal mirror. The spectrum profile of the input pulse is Gaussian with a central wavelength 1054 nm and a FWHM 7 nm. The diameter of the laser beam at the stretcher is 3 mm. We simulate the amplifier doesn't change the central wavelength and the Gaussian profile, but narrows the FWHM from 7 nm to 3.4 nm. For the compressor, the grating constant is 1740 g/mm, the perpendicular distance between the two parallel gratings is 1850 mm, the diameter of the laser beam is 320 mm, and the angle of incidence is 70^0. The focal length of the off-axis paraboloidal mirror is 800 mm.

As is given by the Eq. (2) and Eq. (4), the wavelength-dependent clipping ratios of energy $k_c(\lambda)$ and $k_s(\lambda)$ are determined by the bandwidth of the compressor $\delta\lambda_c$ and the bandwidth of the stretcher $\delta\lambda_s$, respectively. $\delta\lambda_c$ and $\delta\lambda_s$ are symmetrical to the central wavelength 1054nm. When $\delta\lambda_c/\delta\lambda=0$, $\delta\lambda_c/\delta\lambda=2$, $\delta\lambda_s/\delta\lambda=2$ and $\delta\lambda_s/\delta\lambda=4$, the wavelength-dependent clipping ratios of energy are presented in Fig. 2, where $\delta\lambda$ is the FWHM of the amplified pulse. We can calculate the intensity temporal profile of the recompressed pulse by solving the Eq. (6). The results are given in Fig. 3, which shows the inverse Fourier transform of the output spectrum clipped by the clipping ratios $k_s(\lambda)$ and $k_c(\lambda)$ presented in Fig. 2. In Fig. 3a/3b, the stretcher allows $2\delta\lambda$ to pass ($\delta\lambda_s/\delta\lambda=2$), and in Fig. 3c/3d, the stretcher allows $4\delta\lambda$ to pass ($\delta\lambda_s/\delta\lambda=4$). Dot line describes $2\delta\lambda$ pass the compressor without being clipped ($\delta\lambda_c/\delta\lambda=2$), and solid line describes $0\delta\lambda$ pass the compressor without being clipped ($\delta\lambda_c/\delta\lambda=0$). In Fig. 3a/3c the pulse duration is 590-fs/480-fs, which indicates that the pulse duration is influenced by the bandwidth of the stretcher. However, the pulse duration is related to the bandwidth of the amplified pulse $\delta\lambda$, the spectral clipping in the amplifier (the gain narrowing and the gain saturation in the amplifier are treated as a kind of spectral clipping effect) is the only factor determine the pulse duration. Besides, in Fig. 3b the wings of the recompressed pulse appear at $10^{2.5}$ level, which is slightly better when $\delta\lambda_c/\delta\lambda=0$ than $\delta\lambda_c/\delta\lambda=2$. Similarly, the wings of the recompressed pulse appear at 10^6 level in Fig. 3d, which is slightly worse when $\delta\lambda_c/\delta\lambda=0$ than $\delta\lambda_c/\delta\lambda=2$. The result shows that the intensity temporal contrast ratio of the recompressed pulse is determined by the rate $\delta\lambda_s/\delta\lambda$. The bandwidth of the compressor does influence the intensity temporal contrast ratio. When $\delta\lambda_s/\delta\lambda$ is big, it can be improved by increasing the second grating size of the compressor slightly. Contrarily, when $\delta\lambda_s/\delta\lambda$ is small, it can be improved by reducing the second grating size of the compressor slightly. However, this influence is significantly small which can be ignored generally.

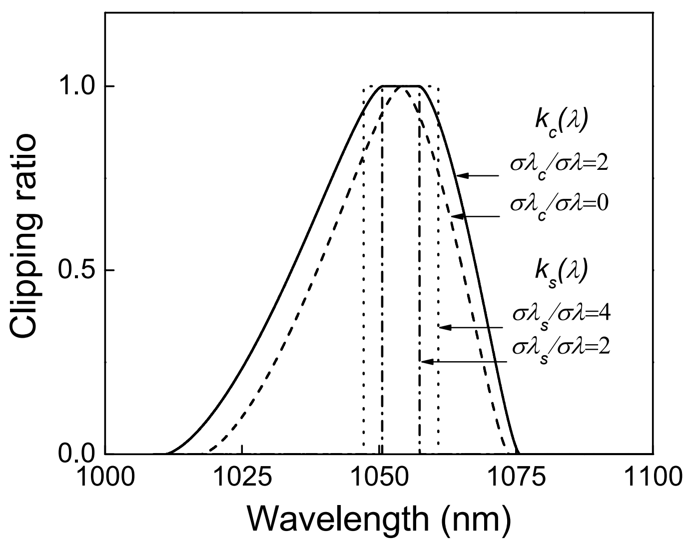
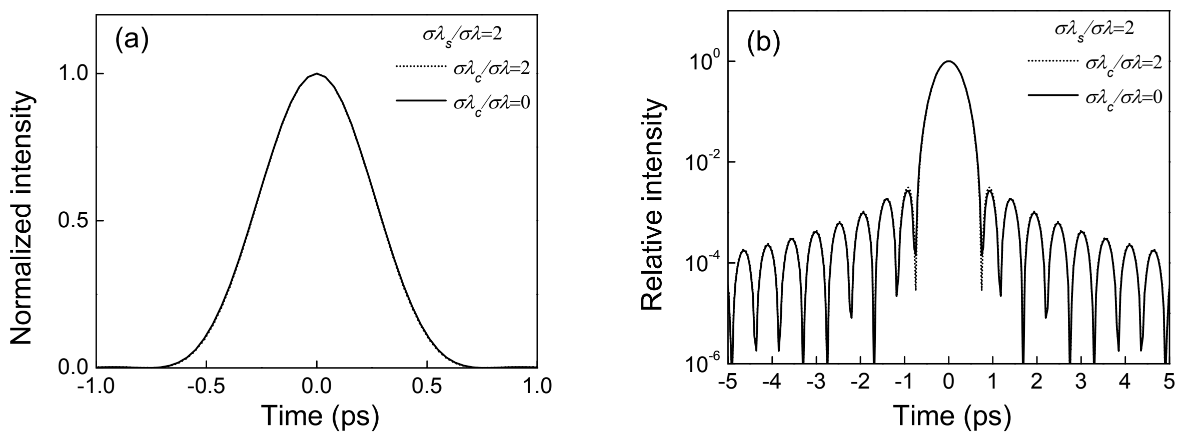


Fig. 2. Wavelength-dependent clipping ratio of energy at stretcher/compressor. Dash-dot line and dot line, clipping ratios at the stretchers with bandwidths $\delta\lambda_s=2\delta\lambda$ and $\delta\lambda_s=4\delta\lambda$, respectively; dash line and solid line, clipping ratios at the compressors with bandwidths $\delta\lambda_c=0$ and $\delta\lambda_c=2\delta\lambda$, respectively



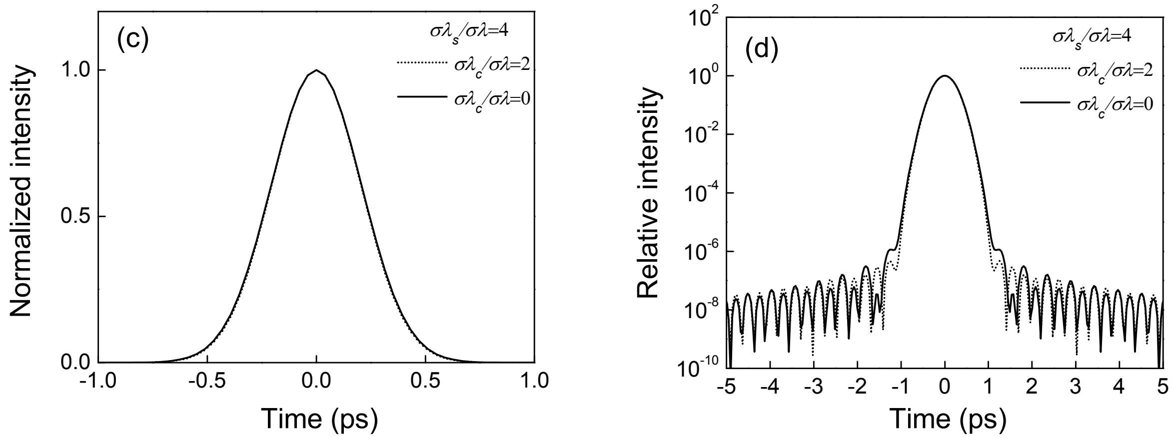


Fig. 3. Intensity temporal profile of the recompressed pulse. (a)/(c) and (b)/(d), linear and logarithmic plot; (a)/(b) and (c)/(d), the bandwidths of the stretchers are $\delta\lambda_s=2\delta\lambda$ and $\delta\lambda_s=4\delta\lambda$, respectively; solid line and dot line, the bandwidths of the compressors are $\delta\lambda_c=0$ and $\delta\lambda_c=2\delta\lambda$, respectively

4. CONCLUSIONS

We investigate the spectral clipping effect in a chirped pulse amplification laser system and present a theoretical model. Using this model, the wavelength-dependent spectral clipping ratios in different stretcher-compressor designs are calculated. And then the recompressed pulse's temporal distribution is analyzed. The result indicates that the temporal contrast ratio is determined by the stretcher and the amplifier. The pulse duration is determined by the amplifier and influenced by the stretcher. Despite that the compressor can ameliorate or aggravate the temporal contrast ratio based on different stretchers and amplifiers, the influence is so slight that it can be ignored.

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