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Offner stretcher aberrations revisited to compensate material dispersion

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A B S T R A C T

We present simple analytical formulae for the calculation of the spectral phase and residual angular dispersion of an ultrashort pulse propagating through the Offner stretcher. Based on these formulae, we show that the radii of curvature of both convex and concave mirrors in the Offner triplet can be adapted to tune the fourth order dispersion term of the spectral phase of the pulse. As an example, a single-grating Offner stretcher design suitable for the suppression of material dispersion in the Ti:Sa PALS laser system is proposed. The results obtained by numerical raytracing well match those calculated from the analytical formulae.

1. Introduction

With the chirped pulse amplification (CPA) technique, ultrashort laser pulses can be amplified to the PW scale [1–4]. Since modern laser systems aim at a temporal contrast up to 10^{-12} with minimal pulse broadening to avoid ionization of the experimental targets, it is essential that the spectral phase of ultrashort pulses is precisely controlled. To describe the effect of the residual spectral phase on the temporal profile of a pulse, the phase is usually expanded in a Taylor series about the central frequency. While the second derivative of the phase (group delay dispersion — GDD) mostly induces pulse broadening, the third (third order dispersion — TOD) and the fourth (fourth order dispersion — FOD) derivatives also influence the pulse contrast. To reach transform-limited pulses shorter than 100 fs, it is crucial to be able to adjust each dispersion order individually.

There are two main sources of residual spectral phase in CPA systems — the material dispersion present mainly in the amplification chain (crystals, windows, etc.) and the aberrations of the stretcher imaging system [5]. While the material dispersion cannot be avoided, the stretcher aberrations can be eliminated with a two-grating Offner stretcher design [6]. The material GDD and TOD can be compensated by tuning of the angle of incidence on the gratings and the distance between the gratings in the stretcher or compressor. The residual FOD can then be suppressed by lowering the line density of the stretcher gratings [5] or by taking advantage of the aberrations present in the stretcher imaging system, as in the Banks design [7]. In general, these methods are not suitable for all systems, as the line density tuning offers only a relatively small FOD correction while the Banks design correction is usually too large. Also, the line density of the gratings required for FOD compensation may not be commercially available. For these reasons, some other methods have recently been proposed such as the addition of a grism pair between the stretcher and the compressor [8]. Active compensation is also possible with an acousto-optic modulator, but its range is also limited [9].

We propose a simple passive method for the correction of residual FOD based on a subtle modification of the Offner stretcher imaging system. This method extends the work of Zhang [10] and Molander [11], who purposefully introduced aberrations into the imaging system of the Offner stretcher to compensate the residual phase of the pulse. The aberration-free Offner stretcher is composed of 2 gratings with an Offner triplet in between wherein the first grating lies at the centre of curvature of the first concave mirror. There are two simple possibilities for the introduction of some additional spherical aberration in this design — the first grating can be shifted closer to the first concave mirror [Zhang] or the radius of curvature of the convex mirror can be adjusted [Molander]. Both of these modifications retain the 1:1 magnification of the imaging system and the collimation of the beam, but they increase the spherical aberration of the stretcher and they can be used advantageously to compensate the residual FOD. These methods can be easily combined in a single grating Offner stretcher configuration discussed in the next section.

2. Theory

We employ the analytical theory which connects the Seidel aberrations with the spectral phase dispersion terms of the ultrashort

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Table 1
Aberration coefficients of an Offner triplet calculated according to the aberration theory presented in [12], where B is a coefficient for spherical aberrations, C for astigmatism, D for field curvature and F for coma.

Aberr.	$(R_1 = -2R_2)$	$(R_1 \neq -2R_2)$
B (Sph.)	$\frac{(R_1-s)^4}{2R_1^3 s^4}$	$\frac{R_1^8 - 3R_1^7R_2 + 8R_1^6R_2s + 4R_1^5R_2^3 - 16R_1^5R_2^2s + 24R_1^4R_2^2s^2 - 32R_1^3R_2^3s^2 + 32R_1^2R_2^4s^2 + 32R_1^2R_2^3s^3 - 64R_1R_2^4s^3 + 32R_2^4s^4}{8R_1^3R_2^4s^4}$
C (Astg.)	$2\frac{(R_1-s)^2}{R_1 s^4}$	$\frac{R_1^6 - 3R_1^5R_2 + 4R_1^4R_2s + 4R_1^3R_2^3 - 8R_1^3R_2^2s + 4R_1^2R_2^2s^2 + 16R_2^4s^2}{16R_1R_2^4s^4}$
D (FC)	$\frac{(R_1-s)^2}{R_1 s^4}$	$-\frac{-R_1^6 + 3R_1^5R_2 - 4R_1^4R_2s - 4R_1^3R_2^3 + 8R_1^3R_2^2s - 4R_1^2R_2^2s^2 + 16R_1R_2^3s^2 + 16R_2^4s^2}{32R_1R_2^4s^4}$
F (Coma)	$-2\frac{(R_1-s)^3}{R_1^2 s^4}$	$-\frac{R_1^7 - 3R_1^6R_2 + 6R_1^5R_2s + 4R_1^4R_2^3 - 12R_1^4R_2^2s + 12R_1^3R_2^2s^2 - 16R_1^2R_2^3s^2 + 16R_1R_2^4s^2 + 8R_1R_2^3s^3 - 16R_2^4s^3}{16R_1^2R_2^4s^4}$

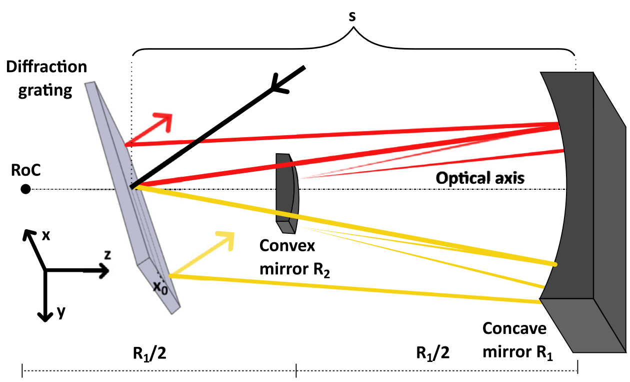

Fig. 1. A general schematic of a single-grating Offner stretcher. The object is defined as the place where the pulse hits the diffraction grating. The X-axis is parallel with the grating grooves, the Y-axis is perpendicular to the grating grooves and the optical axis of the Offner triplet. The origin of the coordinate system is the intersection of the grating plane and the optical axis of the imaging system.

pulse [13]. The analytical formulae are derived within the linear approximation of the grating dispersion with respect to the frequency and with the assumption that the pointing of the diffracted central frequency component of the pulse is parallel with the optical axis of the stretcher imaging system. If the imaging system has, for example, a spherical aberration, then each frequency component acquires an additional optical path distance which has a quartic dependence on the radial distance from the optical axis at the entrance pupil (located at the first concave mirror). Here, we review the main formulae and apply them to the Offner stretcher. A general schematic of the Offner stretcher with the coordinate system definition is sketched in Fig. 1. In this paper, only a 2-pass stretcher design[1] is discussed which allows for the assumption that the y offset in the diffraction plane is zero. All dependence on y_0 will therefore be omitted in the following calculations.

The FOD deviation FOD^{ab} can be calculated using the spherical aberration coefficient B and does not depend on the x or y offsets of the object:

$$\begin{aligned}\mathrm{FOD}^{ab} &\doteq 24Bs^4 \frac{m^4N^4(2\pi)^4c^3}{\omega_0^7\cos^4(\beta_0)} \\ &\overset{(R_1=-2R_2)}{=} 12\frac{(R_1-s)^4}{R_1^3}\frac{m^4N^4(2\pi)^4c^3}{\omega_0^7\cos^4(\beta_0)},\end{aligned} \tag{1}$$

where m is the diffraction order, N is the line density of the grating, ω_0 is the central frequency of the pulse, β_0 is the diffraction angle of the ray at central frequency, s is the distance from the grating to the first mirror and c is speed of light. The GDD deviation GDD^{ab} is induced by the interplay of the spherical B, field curvature D and coma F coefficients and grows quadratically with the x_0 offset:

$$\begin{aligned}\mathrm{GDD}^{ab} &\doteq 2x_0^2(2B+D+F)s^2\frac{m^2N^2(2\pi)^2c}{\omega_0^3\cos^2(\beta_0)} \\ &\overset{(R_1=-2R_2)}{=} 2x_0^2\frac{(R_1-s)^2}{R_1^3}\frac{m^2N^2(2\pi)^2c}{\omega_0^3\cos^2(\beta_0)}.\end{aligned} \tag{2}$$

The individual aberration coefficients of the Offner triplet necessary for the evaluation of these formulae are presented in Table 1. The coefficients for the Offner triplet with detuned R_2 are rather complicated and they are better understood graphically. By substitution of the corresponding aberration coefficients from Table 1 into Eqs. (1) and (2), we plot GDD^{ab} and FOD^{ab} profiles as functions of s and R_2 in Fig. 2. With $R_2 = -R_1/2$ the results meet expectations as the aberrations are zero at the centre of curvature of the concave mirror ($s = R_1$) and grow with changes in s. Also, the decrease of the curvature of the convex mirror leads to the decrease of FOD^{ab} and vice versa. Changes in R_2 produce offsets in the GDD^{ab} curves.

For the calculation of the residual angular dispersion of a system with broad bandwidth, it is necessary to abandon the linear approximation. Because there is no derivative with respect to the frequency required in Eq. (10) from [13], the calculation is quite straightforward with $R_2 = -R_1/2$. The residual angular dispersion in the xz plane $\mathrm{d}\theta_x(\lambda)$ and yz plane $\mathrm{d}\theta_y(\lambda)$ can be obtained using aberration coefficients from Table 1:

$$\begin{aligned}\mathrm{d}\theta_y(\lambda) &= \frac{\cos(\beta_0)}{\cos(\alpha)}\frac{\mathrm{d}(Bs^4\theta(\lambda)^4 + x_0^2(2B+D+F)s^2\theta(\lambda)^2)}{\mathrm{d}s}\frac{1}{\theta(\lambda)} \\ &\overset{(R_1=-2R_2)}{=} 2\frac{\cos(\beta_0)}{\cos(\alpha)}\left(x_0^2\frac{(s-R_1)}{R_1^3}\theta(\lambda) - \frac{(R_1-s)^3}{R_1^3}\theta^3(\lambda)\right); \\ \mathrm{d}\theta_x(\lambda) &= \frac{\mathrm{d}(x_0^2(2B+D+F)s^2\theta(\lambda)^2)}{\mathrm{d}x_0} \\ &\overset{(R_1=-2R_2)}{=} 2x_0\frac{(R_1-s)^2}{R_1^3}\theta^2(\lambda),\end{aligned} \tag{3}$$

where α is the angle of incidence and $\theta(\lambda)$ is the angular deviation of the wavelength component with respect to the central wavelength of the pulse. The formulae for angular dispersion with arbitrary R_2 can be calculated in the same manner using coefficients from Table 1, but we omit them here for the sake of clarity as they are very long and do not offer much physical insight. According to the formulae for the dispersion of an ideal stretcher/compressor [5], the residual GDD and TOD from material dispersion can be compensated if we increase the distance s and decrease the angle of incidence α in the stretcher. By this adjustment, the deviation of the residual FOD is increased even more due to the different GDD/TOD/FOD ratios of the diffraction grating and the material dispersion. To compensate this, it is necessary to substitute a certain spherical aberration coefficient $B(R_1, R_2, s)$ into Eq. (1) so that the residual FOD equals FOD^{ab}. In general, it is better to keep R_2 fixed to $-R_1/2$ to minimize the residual angular dispersion. However, in some cases, especially if the calculated R_1 is approaching ~ 1 m or less, the aberrations originating from the x_0 offset become relatively significant. Then, it can be beneficial to detune R_2 from the original value while

[1] By 2-pass design we mean that the pulse is diffracted by the grating 4 times in total.