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Measurement of non-compensated angular dispersion and the subsequent temporal lengthening of femtosecond pulses in a CPA laser

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Abstract

Closed analytical formulae are given for the residual angular dispersion resulted from the non-parallel surfaces of both a grating pair and a prism pair pulse compressor. Accurate measurements of the angular dispersion of pulses leaving the misaligned pulse compressors agree well with the first principle simulation curves. The corresponding lengthening of the transform limited 18 fs pulses was also determined. Finally, it is experimentally proved that by simultaneous monitoring of angular dispersion and pulse duration, the stretcher–compressor system of a chirped pulse amplification laser can be aligned very precisely.

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Keywords: Ultrafast lasers; High intensity lasers; Pulse compression; Chirping

1. Introduction

The non-parallelism of the grating planes of a stretcher–compressor system of a high power chirped pulse amplification (CPA) laser introduces residual angular dispersion into the laser beam approaching the target. A similar effect can be observed in other experiments where femtosecond pulses directly from a laser oscillator are compressed by a prism pair with slightly non-parallel surfaces or passes through small wedges like glass filters or beam splitters.

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As it is known, angular dispersion, defined by the angle between the spectral phase fronts, makes the pulse temporally chirped and its pulse front tilted [1,2]. In case of plane waves, the former is proportional to the propagation length [3], hence can be compensated by changing the distance between the gratings only for a given target distance [4,5]. However, the pulse front tilt still remains and causes a longer illumination of the target than the pulse duration itself [6,7]. This effect is more severe for large aperture beams. Several papers have been dealing with these issues and established only theoretical tolerances for the parallelism of the gratings [8–10] and prisms [11,12] of pulse compressors. Relatively simple to use devices have been proposed for synchronous determination of pulse front tilt and pulse duration [13–16]. Since all of them are based on non-linear techniques, even the most current version is limited for pulses not shorter than 20 fs [17]. Some of them [15,16] have been already demonstrated to help in the alignment of a CPA laser system but the latter provides only qualitative information while the former is fairly inaccurate in terms of angular dispersion. For the high precision measurement of angular dispersion itself, however, linear methods have been more recently developed for both spatially Gaussian beams and for plane waves [18–20].

In this paper we present, to our knowledge, the first experimental proof of the analytical expressions of residual angular dispersion resulted from the misalignment of both a grating pair and a prismatic pulse compressor. We also present the first systematic experiment to point out that the combination of the measurement of residual angular dispersion with the synchronous monitoring of the pulse length is an efficient way for the accurate alignment of pulse compressors.

2. Residual angular dispersion

2.1. Grating compressor

Fig. 1 shows a sketch of a usual pulse compressor consisted of two identical diffraction gratings. The operation of such a system has been detailed and analyzed in several papers [2–4,7–9], so here we emphasize the basic and necessary points only. A laser beam entering the system is diffracted and angularly dispersed by the first grating. In an ideal case the second grating compensates for the angular spreading of each spectral component providing the same angular dispersion as the first grating but with an opposite sign. Hence, the spectral components propagate parallel to each other towards the end mirror M. After reflection the rays follow the same path but in reverse order, resulting in a collimated output beam and a laser pulse with substantially changed spectral phase. The second and third order derivatives of the spectral phase are the group delay dispersion (GDD) and third order dispersion (TOD), respectively, which are responsible for the temporal shape and contrast of the pulse [3,21–24].

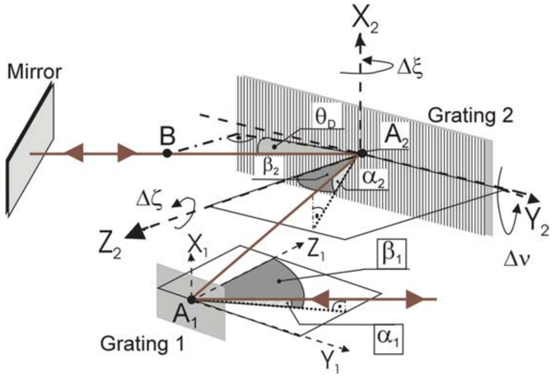

Fig. 1. A grating pair compressor with the definition of the rotation axes of the grating planes.

Problems start rising when the spectral rays leaving the second grating are not strictly parallel to each other, which means that the beam is angularly dispersed. Using the arguments and notations of [8], such residual angular dispersion of a grating pair can be calculated as follows.

Let's assume that the first grating stands in the laboratory such that the laboratory vertical axis X_1 is parallel to the grating grooves, the plane X_1–Y_1 is parallel to the grating surface, and the Z_1–Y_1 plane is parallel to the horizontal axis of the laboratory. In a well aligned case, the axes of the second grating X_2, Y_2 and Z_2 are parallel to X_1, Y_1 and Z_1, respectively. An arbitrary position of the second grating with respect to the first one can hence be described as a rotation around its axes by $\Delta\xi$, $\Delta\upsilon$ and $\Delta\zeta$. The former two results in slanting and tilting of the second grating, respectively, while $\Delta\zeta$ makes the grooves of the second grating non-parallel to the first one's. Angular dispersion of the beam leaving the second grating can be fully described by its projection onto two perpendicular planes. In the "diffraction plane", that is the Y_1–Z_1 plane of the first (standing) grating, the residual angular dispersion is

$$\frac{d\theta_D}{d\lambda} = -\frac{1}{\cos\delta_2'\cos\beta_2'}\left\{\sin\alpha_2\left(1+\sin\beta_2\sin\beta_2'\right)\frac{d\alpha_2}{d\lambda} + \sin\beta_2'\left(m_2-\cos\alpha_2\cos\beta_2\frac{d\beta_2}{d\lambda}\right)\right\}, \quad (1)$$

where $d\beta_2/d\lambda$ is a function of $\Delta\xi$, $\Delta\upsilon$ and $\Delta\zeta$ [8]. In the "perpendicular plane" to Y_1–Z_1, which contains the optical ray of the exiting pulse at perfect alignment, the spectral divergence of the rays is given by

$$\frac{d\theta_P}{d\lambda} = \frac{d\alpha_2'}{d\lambda} = \frac{m_1}{\cos\alpha_2\cos\beta_1'}\left\{\sin\Delta\zeta\cos(\beta_1'-\Delta\xi) - \cos\Delta\zeta\sin(\beta_1'-\Delta\xi)\sin\Delta v\right\}. \quad (2)$$

Here the indices 1 and 2 refer to the first and second grating, respectively, and the effective groove density m is calculated from the diffraction order j and the groove width d as $m = j/d$. For most compressors the two gratings are identical and $m_1 = m_2$. The diffraction angles α' and β' are calculated from the grating equations

$$\sin\alpha' = -\sin\alpha \text{ and } \sin\beta+\sin\beta' = \frac{m\lambda}{\cos\alpha},$$

while $\sin\delta_2' = \cos\alpha_2'\cos\beta_2'$ [8].

In the presence of residual angular dispersion the performance of a grating pair is different from the one which designed, since its phase shift ϕ will depend on the amount of residual angular dispersion. The commonly regarded most crucial alignment is the slanting (turning around ε_X) of the second grating. In the presence of "diffraction plane" residual angular dispersion only, the GDD and TOD of a grating pair from the first grating (point A_1) to the point B can be hence expressed as [8]

$$\mathrm{GDD_G} = \frac{d^2\phi}{d\omega^2} = -\frac{\lambda^3 L_G}{2\pi c^2\cos^2\beta_2}\left[\frac{m_1 m_2}{\cos\beta_1'} - \frac{m_1\sin\delta_2'}{\cos\beta_1'}\frac{d\theta_D}{d\lambda} - \cos\beta_2\cos\left(\beta_2-\beta_2'\right)\left(\frac{d\theta_D}{d\lambda}\right)^2\right] \quad (3)$$

and

$$\mathrm{TOD_G} = \frac{d^3\phi}{d\omega^3} = \frac{3\lambda}{2\pi c}\mathrm{GDD_G} - \frac{\lambda^5 L_G m_1}{4\pi^2 c^3\cos^2\beta_2\cos\beta_1'} \times\left[\frac{2\left(m_2-\sin\delta_2'\right)-\cos\left(\beta_2-\beta_2'\right)\sin 2\beta_2}{\cos\beta_2} - \frac{3m_1 tg\beta_1'\sin\delta_2'}{\cos\beta_1'}\frac{d\theta_D}{d\lambda} + \left(\cos\left(\beta_2-\beta_2'\right) - 3\cos\delta_2'\right)\left(\frac{d\theta_D}{d\lambda}\right)^2 - \sin\delta_2'\frac{d^2\theta_D}{d\lambda^2}\right] + \frac{3L_G\lambda^5\cos\left(\beta_2-\beta_2'\right)}{4\pi^2 c^3\cos\beta_2}\frac{d\theta_D}{d\lambda}\left(\frac{d\theta_D}{d\lambda}+\frac{d^2\theta_D}{d\lambda^2}\right), \quad (4)$$

where c is the light velocity in vacuum and L_G is the distance between the gratings. If the gratings are parallel then L_G denotes the perpendicular distance, otherwise the more general $L_G = A_1A_2\cos\beta_2$ definition is to be used. Since the GDD and TOD are in definition resulted from the Taylor-series of the phase shift around a certain frequency of ω_0 [3], all the derivatives and angles in Eqs. (3) and (4) are taken at ω_0. Please note that the similar Eqs. (28) and (29) of [8] contained many typing errors [25,26] which led even to fatal misinterpretation [27,28]. In accordance with [27] we believe that the present Eqs. (1)–(4) are the correct ones.

It is interesting to calculate the GDD and TOD for a real CPA laser. Here the grating pair is used as a pulse compressor, i.e., the beam reflected back by a mirror, and the target is located at a distance L_T from the compressor. Allowing only small deviation from perfect parallelism ($\Delta\xi$, $\Delta\upsilon$, and $\Delta\zeta < 5°$), the residual angular dispersion of the outcoming beam would be in good approximation the double of Eqs. (1) and (2). In addition, we have to consider that the GDD and TOD of an angularly dispersed plane wave increase with distance [3,4]. This effect has to be taken into account within the compressor between point B and the mirror M at a distance of L_M as well as in the output beam between point A_1 and the target L_T away. Hence, the resulting total phase derivatives are

$$\mathrm{GDD} = 2\mathrm{GDD_G} - \frac{\lambda^3}{\pi c^2}\left(\frac{\mathrm{d}\theta_D}{\mathrm{d}\lambda}\right)^2 (L_M + L_T),$$
$$\mathrm{TOD} = 2\mathrm{TOD_G} - \frac{6\lambda^4}{4\pi^2 c^3}\left(\frac{\mathrm{d}\theta_D}{\mathrm{d}\lambda}\right)^2 (L_M + L_T). \tag{5}$$

Please note that these results may have serious consequences to the performance of a CPA laser. Namely, the alignment of the compressor aims the compensation of the total dispersion of the laser system. If the compressor exhibits residual angular dispersion then the complete compensation is achieved at the position of the pulse width measuring device only. If its distance from the compressor significantly differs from the target distance L_T, then the pulse duration on the target would be longer and the intensity smaller than expected.

2.2. Residual angular dispersion of a prism pair compressor

It is very common that small amount of dispersion is compensated by a prismatic pulse compressor instead of a grating one. This arrangement is typical in experiments using laser pulses directly from a femtosecond oscillator and also in some sub-TW laser systems [29]. Similarly to a grating compressor, non-parallelism of the refractive surfaces of the prisms leads to uncompensated angular dispersion. If a laser beam propagates e.g. along a horizontal plane of the laboratory, the refractive surfaces the prism sequence can be made parallel to the vertical laboratory axis with high precision, so the residual angular dispersion in the "perpendicular plane" can be neglected.

In the "refraction plane", non-parallelism Δ_m of the surfaces means that there is a difference between the emerging angle from the $(m-1)$th prism and the incidence angle on the mth prism (Fig. 2), that is

$$\alpha_m - \beta'_{m-1} = \Delta_m. \tag{6}$$

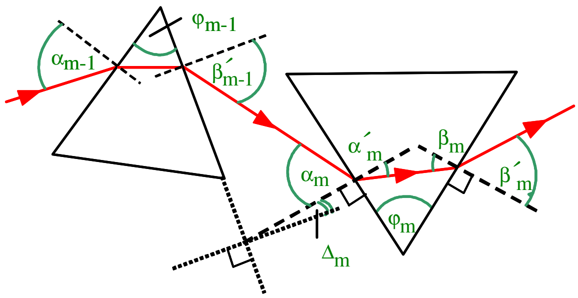

Fig. 2. A prismatic pulse compressor in the most frequent arrangement. If $\Delta_m \neq 0$, then it exhibits residual angular dispersion.

For the "refraction plane" angular dispersion of the mth prism in a prism sequence, after some algebra a successive formula can be derived from Duarte's original equation [11] as

$$\frac{\mathrm{d}\beta'_m}{\mathrm{d}\lambda} = \frac{\sin\varphi_m}{\cos\alpha'_m \cdot \cos\beta'_m}\frac{\mathrm{d}n_m}{\mathrm{d}\lambda} - \frac{\cos\alpha_m \cdot \cos\beta_m}{\cos\alpha'_m \cdot \cos\beta'_m}\frac{\mathrm{d}\alpha_m}{\mathrm{d}\lambda}, \tag{7}$$

where α_m and β'_m are the incidence and emergence angles, n_m is the refractive index and α'_m and β_m are the corresponding angles of refraction (Fig. 2).

It is difficult and complicated to give a closed form for a general prism sequence. For the most widely used setup, however, when a laser beam passes a Brewster prism pair at incident angles close to minimal deviation, a simple equation can be derived. So, after some algebra again, the residual angular dispersion of a prism pair with a non-parallelism Δ of the surfaces can be expressed from Eqs. (6) to (7) as

$$\frac{\mathrm{d}\theta_R}{\mathrm{d}\lambda} = -4\frac{\mathrm{d}n}{\mathrm{d}\lambda}\left[\left(n - \frac{1}{n^3}\right)\Delta + \left(n - \frac{1}{n^3}\right)^2 \Delta^2\right]. \tag{8}$$

Please note that for $\Delta \leqslant 3°$ Eq. (8) approximates the exact value obtainable from the subsequent application of Eq. (7) within 6% accuracy.

3. Experimental

In our experiment pulses at 800 nm with a transform limited length of 18 fs from a Ti:S oscillator of a TW laser [30] have been used (Fig. 3). Upon measuring the grating compressor, the pulses propagated through a Faraday rotator and an all reflective pulse stretcher consisting of two gratings of 1200 l/mm and a 30 cm diameter spherical mirror with a radius of curvature (ROC) of 1000 mm. The design of our stretcher made possible to decrease pulse front distortion below 1 fs, which is otherwise a much more pronounced effect of other pulse stretchers [31]. The beam was then magnified in a 1:4 telescope and sent into the two pass, 1200 l/mm grating compressor at an angle of incidence of $\alpha_1 = 33.1°$. The distance between the parallel gratings, between the mirror M and the point B and, for the outcoming beam, between the point A_1 and the target position of the autocorrelator was $L_G = 37.5$ cm, $L_M \approx 0.20$ m and $L_T \approx 3.5$ m, respectively. In order to make the alignment of both the stretcher and the compressor as precise as possible, in both devices 50% beam splitters were used to align the in- and outcoming beams onto each other.

For the characterization of a prismatic compressor the pulses from the Ti:S oscillator were sent directly through two 68° fused silica prisms at a separation of $L_p = 122.2$ cm and retro reflected by the end mirror (Fig. 3). Again, a beam splitter was used to steer the beam towards the diagnostics.

The angular dispersion has been measured by an imaging spectrograph [19] consisting of a 650 l/mm grating, two air-spaced achromats (collimator: $f = 50$ mm, objective: $f = 100$ mm) and a CCD camera (EDC2000N). The laser beam was focused to the entrance slit by an Ag spherical mirror (ROC = 1 m). As the spectral components of a laser pulse with angular dispersion propagate into different directions, they are separated in the focal plane of the spherical mirror i.e., in the plane of the entrance slit. Thus, they reach the slit at different positions depending on the value of angular dispersion. As a consequence, a tilted spectrum is obtained in the image plane of the spectrograph, that is, if the slit is parallel to the laboratory X_1-axis, then in the λ-X_1 plane (see the inset of Fig. 3.). Please note, that the imaging spectrograph prints directly the angular dispersion in the function of wavelength. Hence, any deviation of the spectrogram from linear is the obvious sign of the presence of second and higher order angular dispersion [18]. The focal length of the mirror and the lenses were chosen to achieve the highest precision for the measurement of the angular dispersion which was established to be ±0.2 μrad/

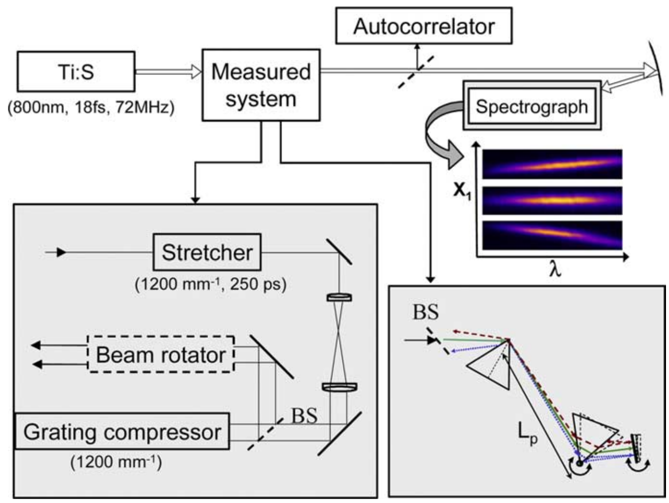

Fig. 3. A schematic of the experimental setup. The inset shows the two-dimensional spectral image of a laser beam having positive (top), zero (middle) and negative (bottom) angular dispersion, when the entrance slit of the spectrograph is parallel to the laboratory X_1-axis.

nm [19]. Due to its construction, the spectrograph was able to determine the angular dispersion only along the plane parallel to the entrance slit. A misaligned grating pair can, however, cause residual angular dispersion along any directions in the plane perpendicular to the propagation direction of the beam. In order to record the angular dispersion for two perpendicular directions, a dog leg has been constructed by using two more beam splitters, which rotates the beam by 90°.

A multiple shot second order interferometric autocorrelator based on GaAsP Hamamatsu G1116 photodiode [32] was used for measuring the duration of the laser pulses. The spectrum was recorded simultaneously, so the temporal shape of the pulses could be retrieved by fitting the autocorrelation traces [33]. This technique provided us with appropriate information on both the duration and the spectral phase shift, up to the third order, of the laser pulses. Hence, this arrangement allowed us to trace any temporal lengthening caused by residual angular dispersion. Due to the necessary geometry of the setup and the extensive losses in the stretcher, compressor and in the beam splitters, the intensity of even the transform limited pulses decreases significantly. As a consequence, the autocorrelator was unable to determine reliably the duration of pulses stretched, and hence their intensity is further dropped, by residual angular dispersion larger than ±12 μrad/nm.

4. Results

4.1. Grating compressor

Initially the stretcher was aligned to exhibit no measurable angular dispersion along both planes. Then the alignment of the pulse compressor was first done using commonly used methods, that is, by accurate geometrical positioning of the gratings and measurement of the duration and phase of the outcoming pulse. In our case the former meant that parallelism of the gratings was carefully checked by ensuring that both the incident and the diffracted rays are horizontal (tilting of the gratings, i.e., turning around Y_2) and the observable higher order diffraction spots lie along a horizontal line (alignment of the grating grooves, i.e., turning around Z_2).

The alignment of the second grating to be parallel to the first one along the diffraction plane (rotation around X_2) was achieved by measuring the duration and phase of the compressed pulse. Following from Eq. (3) at each rotational position of the second grating the distance between the gratings was also corrected to obtain the shortest pulse length. In the same time the residual angular dispersion in the diffraction plane was also recorded. Fig. 4 shows the retrieved pulse width as a function of the measured angular dispersion. As it can be seen, the shortest pulse duration, which is longer than the transform limited value, was obtained at a modest, but well measurable angular dispersion of −2.5 μrad/nm.

Since there was no other angularly dispersive element in the beam between the compressor and the autocorrelator, this result can be explained only by assuming that our classical alignment was not precise enough having left $\Delta\upsilon$ and $\Delta\zeta$ different from zero. Namely, if the diffraction plane angular dispersion was zero then it must have been only the angular dispersion in the perpendicular plane, acting like a single element angular disperser, which made the pulse longer than its transformation limited duration. Following from Eqs. (1) to (2), moreover, there should be an optimum of $\Delta\xi$ for this alignment of $\Delta\upsilon$ and $\Delta\zeta$ where the

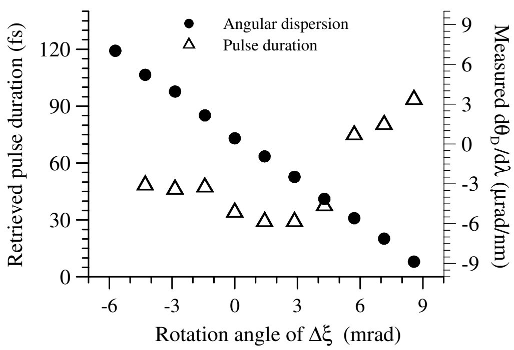

Fig. 4. The retrieved pulse length and residual angular dispersion of a grating pair compressor vs. the rotation of the second grating with respect to the assumed best position of a classical alignment procedure.

pulse lengthening due to both residual angular dispersions is minimal, but still longer than the transform limited duration of 18 fs. The compressor was then aligned to zero angular dispersion by 3D movement of the second grating to simultaneously obtain the transform limited pulse duration and to make the angular dispersion zero along both planes.

In order to validate Eqs. (1) and (2) resulted from our modeling, the second grating has been rotated around its X_2, Y_2 and Z_2 axes, starting from the most accurately aligned position described above. The end mirror had to be also adjusted in order to keep the beam retro-reflected through the system. Both the resulting diffraction plane and perpendicular plane angular dispersions were measured and are displayed in Fig. 5. The corresponding theoretical values have been calculated from Eqs. (1) to (2) using the accurate reading of the grating rotations. Although no free parameters have been used at the generation of the first principle simulation curves but the agreement between the calculated and measured data is excellent. When only the slanting of the second grating is different from zero, then the diffraction plane angular dispersion can reach large values but the one in the perpendicular plane is kept zero (Fig. 5(a)). At pure tilting ($\Delta\upsilon \neq 0$, $\Delta\zeta = 0$) or turning ($\Delta\upsilon = 0$, $\Delta\zeta \neq 0$) of the second grating (Fig. 5(b) and (c), respectively) large perpendicular plane angular dispersion is caused along with a small but still measurable residual angular dispersion also in the plane of diffraction. It is worth noting, that according to the theory [8], the effects of Y_2 and Z_2 rotations can cancel each other. For example, a tilt of the grating by $\Delta\upsilon = 8.3$ mrad can be compensated by a rotation of the grating groves by $\Delta\zeta = 3.9$ mrad. Similarly to the case of the classical alignment above, however, the diffraction plane residual angular dispersion would in both cases differ from zero.

Thus, a grating pair pulse compressor can be regarded most accurately aligned when the residual angular dispersion stays zero in the perpendicular plane during the rotation of the grating around X_2, and when the diffraction plane angular dispersion is zero simultaneously with the perpendicular plane dispersion upon the rotation around the other two axes.

4.2. Prismatic compressor

The residual angular dispersion of a prismatic pulse compressor was also measured. The vertical prism surfaces were aligned very precisely and the angular dispersion of the system was changed by rotating only the second prism around its apex. Under these circumstances the residual angular dispersion in the perpendicular plane was zero within the error of measurement.

The results are shown in Fig. 6. The theoretical values of angular dispersion were calculated from Eq. (6). The pulse duration was computed via Fourier transformation of the measured spectrum with the theoretical values of GDD and TOD of a prism pair at the measured angle of misalignment

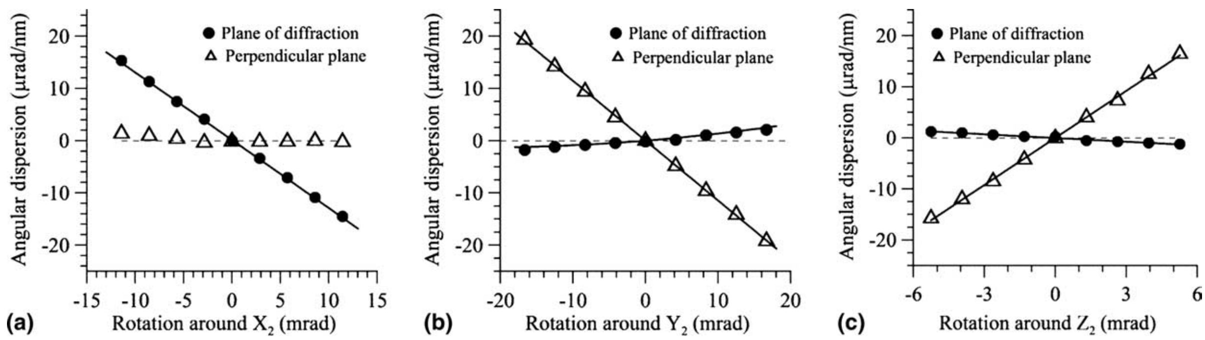

Fig. 5. Measured (symbols) and calculated (curves) values of residual angular dispersion of a grating pair pulse compressor due to rotation around the axes X_2 (a), Y_2 (b) and Z_2 (c).

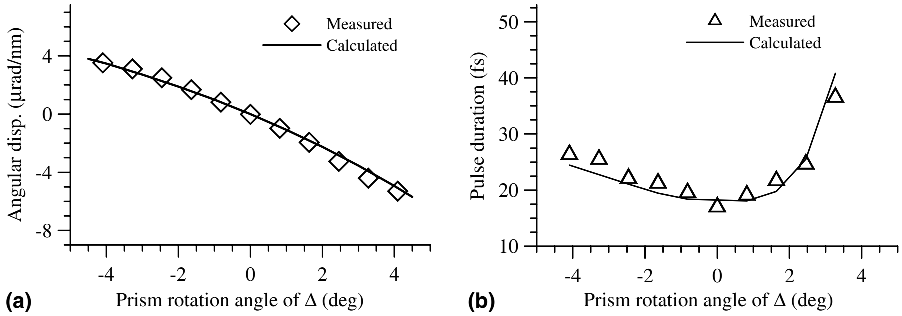

Fig. 6. Residual angular dispersion (a) and the corresponding stretched pulse durations (b) for a prism compressor.

Δ [34]. The agreement between the calculated and measured values in the plane of dispersion is excellent. Note that the pulse duration is quite insensitive to the prism rotation, hence the parallelism of the prism surfaces can be aligned much more precisely by measuring the angular dispersion than by monitoring the pulse length. For instance, an increase of 1 fs in the pulse duration, which could be just distinguished from the transform limited length, was detected at a well resolved angular dispersion of ±1 μrad/nm.

5. Summary

We have calculated the exact formulae of residual angular dispersion of a non-parallel grating pair. For a prism pair, a simple form was derived from the successive form, which provides a good approximation for practical cases. Experiments proved the formulae for both a grating pair and a prismatic pulse compressor, giving an excellent agreement to the first principle simulation curves.

We have also shown that the commonly used way of the fine alignment of a pulse compressor, which is based on the measurement of pulse duration as an ultimate target parameter only, has certain limitations. For a prism pair compressor it gives a compressed pulse duration within ±5% deviation from the transform limited pulse length. For the accurate alignment of a grating pair compressor of TW class-lasers the pulse length measurement has to be combined with the determination of the angular dispersion in two perpendicular directions. This is especially important, because the residual angular dispersion also results in higher order phase derivatives which not only lengthen the pulse duration but also heavily spoil the temporal contrast [23].

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