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Measuring the Relation between Pulse-Front-Tilt Angle and Beam Size for Ultrashort Laser Pulses

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Abstract. In this work we report experimental investigations of an intentionally introduced pulse front tilt on femtosecond laser pulses by using an inverted field interferometer. The results obtained using two low-dispersion diffraction gratings are in good qualitative agreement with the data from a previously developed analytical model and from an independent second-order correlation measurement with an inverted-field correlator.

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1 Introduction

The pulse front tilt (PFT) is a specific spatio-temporal distortion of (ultra)fast optical pulses - the pulse front is tilted with respect to the direction of beam/pulse propagation, while its phase front remains perpendicular to it. In some cases the PFT is useful. When the lifetime of an amplifying medium is shorter than the driving laser pulse, pump pulses with tilted pulse fronts offer the possibility to progressively deposit the pump energy along the gain medium at a speed equal to the transient speed of the amplified wave (see e.g. [1–5]). Another example is the efficient phase-matched terahertz radiation generated by optical rectification of femtosecond laser pulses [6, 7] down to near-single-cycle terahertz pulse durations [8–11]. In high harmonic generation experiments, pulses with tilted fronts enable the production of sources emitting a collection of angularly well-separated light beams, each consisting of an isolated attosecond pulse [12]. However, when PFT is present, the duration of the pulse is short only in a limited region of space [13] and the effective pulse duration increases. Tilting of the pulse front of picosecond pulses after traveling through a prism [14] or diffracting off a grating [15] is well known [13]. The PFT is one of the major issues in chirped pulse amplification systems [16–18], caused by misaligned pulse stretchers and/or compressors. PFT can also occur when femtosecond pulses are focused [19, 20] or passed through birefrigent crystals [21]. Even the overlapping of femtosecond pulses with PFT is not simple anymore [22].

Specific diagnostic techniques for detecting and measuring PFT are available: tilted pulse front autocorrelation [23–25], spectrally resolved interferometry [26], Grating-Eliminated No-nonsense Observation of Ultrashort Incident Laser Light E-fields (GRENOUILLE) [27], and Cross-correlation Frequency-Resolved Optical Gating (XFROG) [28]. The usual interferometric second-harmonic autocorrelators based on Michelson or Mach-Zehnder-type schemes are not able to detect PFT unless one of the beams/pulses is inverted in space [29, 30] or cross-correlation between a tilted and a non-tilted pulse is realized [31]. In such inverted-field (IF) correlators, the delay between the pulses also depends on the particular transverse coordinate across the beam. Hence, the recorded autocorrelation trace contains information on the effective broadening of the ultrashort pulse due to the PFT [30, 32]. However, one has to keep in mind that is such (auto)correlators the crystal for second harmonic generation (SHG) is placed in more or less focused beam which additionally alters the PFT. Moreover, any change in the beam's transverse dimension in the plane of PFT inevitably influences the PFT. This fact, which is supported by the physical intuition, deserves special attention in experiments with ultrashort laser pulses with tilted pulse fronts.

In this work we report experimental investigations of intentionally introduced pulse front tilts on femtosecond laser pulses by using inverted field interferometer with a focusing lens at its exit. The presented results are in a good agreement with these from an independent experiment carried out by using an inverted field SHG correlator.

2 Pulses with Tilted Fronts – Physical Picture

Let us consider the amplitude of a Gaussian beam/pulse shown in Figure 1a. Let assume that the beam/pulse is propagating along the z-axis, parallel to the time axis t, perpendicular to its phase front. For convenience, let us normalize the transverse spatial beam size x to the speed of light c. Hence, the unit of x/c is $[x/c] = 1$ fs and we have the correspondence $1\,\mathrm{fs} \leftrightarrow 0.3\,\mu\mathrm{m}$ for a central wavelength $\lambda_0 = 808\,\mathrm{nm}$ of the pulse spectrum. If the front of this pulse is tilted at an angle F with respect to the phase front (Figure 1b), it will keep propagating in the same direction (perpendicular to the unchanged beam's phase front), however the right part of the pulse envelope outdistances the left part. In this way, considering the complete beam in space, the ultrashort pulse becomes effectively much broader in time.

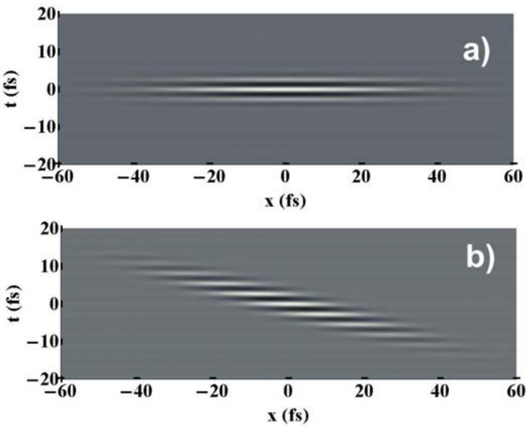

Figure 1. Amplitude of a Gaussian beam/pulse without (a) and with a PFT (b). Propagation takes place along the z-axis, which is parallel to the time axis t.

3 Pulses with Tilted Fronts in an Inverted Field Interferometer

Special feature of this interferometer is that the number of reflections in one of its arms differs from the number of reflections in the other arm by 1 (or by an odd number; see Figure 2). Because one of the interfering beams is rotated by

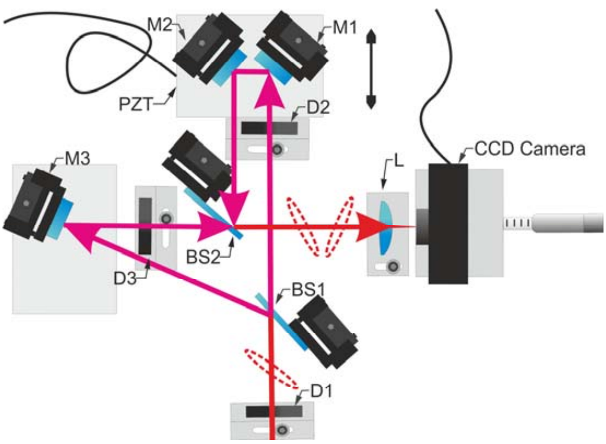

Figure 2. Inverted field interferometer with a focusing lens at its exit. M1...M3 — protected silver flat mirrors, BS1, BS2 — beamsplitters ($45^{\circ}/800$ nm), D1, D2 — iris diaphragms, L — lens ($f = 3.5$ cm), CCD — charge-coupled device camera on a translation table, PZT — piezotransducer-driven translation table. Dashed ellipses — pulses/beams with their respective PFTs.

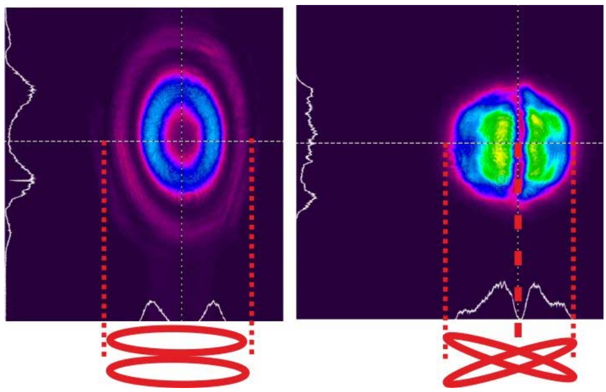

Figure 3. Interference of femtosecond beams/pulses in an inverted field interferometer in the absence (left) and in the presence of a PFT (right).

180° with respect to the second one (around their common propagation axis) they are called inverted field interferometers [18, 29, 30]. In essence, at their exits one gets two specular reflected pulses with the same PFT angles of opposite signs. As a consequence, the interference of such ultrashort pulses takes place in a limited region only, in which the beams/pulses overlap in both space and time [18, 29, 30]. At a non-negligible PFT and ultrashort pulses interference stripes are not to be expected across the whole beam cross section, but within a limited region of the beam only. Naturally, the transverse location of this region of interference depends on the time delay between the optical pulses (see Figure 2 and Figure 3b). In the left frame in Figure 3 we show an experimentally recorded interference pattern of femtosecond beams/pulses in an inverted field interferometer in the absence of PFT. In this case interference fringes are clearly visible across the whole beam aperture. If the PFT is non-negligible anymore (Figure 3, right frame) interference occurs in the region of beam/pulse overlapping only. When the PFT angle is large, it can appear just as a single dark stripe, which is highly space- and delay-dependent.

4 Measurement of the PFT and Its Dependence on the Beam Size

At a fixed position of the CCD camera sensor behind the lens L (see Figure 2), i.e. at a well determined beam size r_j, one has to obtain the dependence of the position X_j of the interference stripe of maximal contrast on the optical propagation path length Z_j (i.e. on the time delay; see Figure 4). In this way one can determine the PFT angle F_j for the j-th beam size:

$$\tan(F_j) = \Delta P/\Delta X = (\Delta Z/2)/\Delta X \tag{1}$$

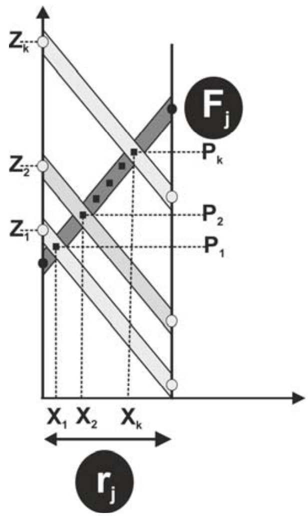

Figure 4. Schematic representation of the measurement of the PFT angle F_j at a beam size r_j for the j-th position of the CCD camera with respect to the lens. The quantities extracted from the measurements are in black circles.

Here ΔZ is the additional beam/pulse propagation path length causing a transverse shift of the interference line at a distance ΔX. In other words, the slope of the dependence $P(X)$ (see Figure 7) is the PFT angle F.

When the pulse front is tilted with respect to the phase front, the PFT angle should depend on the beam size [3]. This is intuitively clear shown in Figure 5. Let assume, that points A and B belong to the same phase front. Shrinking the beam size from r_1 to r_2 will lead to a correspondence of the local intensity in point A to this in point B. This means that the PFT angle F_1 will increase to F_2. If we measure the change ΔX in the position of the interference stripe with maximal contrast vs. the change ΔZ in the optical path length in one of the

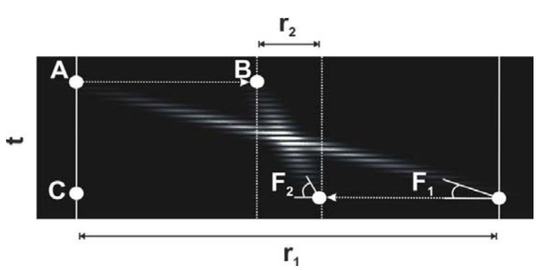

Figure 5. Schematic representation of the change of the PFT angle due to the changed beam size. See text for details.

interferometer arms, determining the PFT angle F_j for different beam sizes r_j (e.g. at different locations of the CCD camera with respect to the lens), one can determine the quantity AC. In essence, AC is a measure for the effective pulse duration. Using the linear relation

$$\tan(F_j) = AC/r_j \tag{2}$$

one can calculate the PFT angle for each particular beam size.

5 Experiment

In this experiment, in order to intentionally introduce PFT in the 80-MHz train of 25-fs pulses (measured at $1/e^2$ intensity level) with a central wavelength of their spectra $\lambda_0 = 808$ nm, we used diffraction gratings (see Figure 6). By means of two flat mirrors (M5 and M6) the pulses are first redirected to the grating. The beam diffracted in first order is sent back on the preliminary fixed propagation path when passing through three diaphragms (D1, D4, D5). This propagation axis is fixed after precise alignment of the interferometer. The two flat mirrors M5 and M6 are mounted on a translation stage. They can be easily removed from the propagation path thus allowing switching from non-zero to zero PFT and vice versa. The interferometer is built with three flat silver mirrors (M1, M2, M3), a pair of beamsplitters (800 nm/45°), two iris diaphragms (D1, D2), lenses L1 with a focal lengths $f = 3.5$ cm, and a charge-coupled device camera (Ophir SP620U, format 1/1.8", pixel size $4.4\ \mu\text{m} \times 4.4\ \mu\text{m}$). The piezo translation stage PZT (nanoX200SG, Piezosystem Jena) with 200 μm scan range is driven by a power supply ENV 40 (Piezosystem Jena) connected to a voltage pulse generator (GW-Instek AGF 2124) and an oscilloscope (Tektronix TDS 2012B).

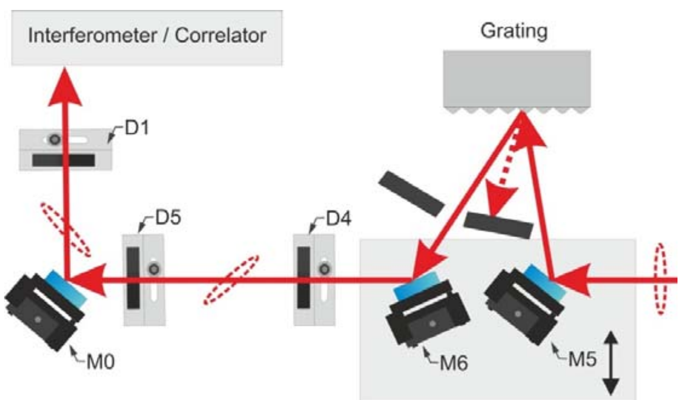

Figure 6. System for tilting the pulse fronts of femtosecond pulses by means of diffraction gratings. Mx - protected silver-coated mirrors, Dx - diaphragms.

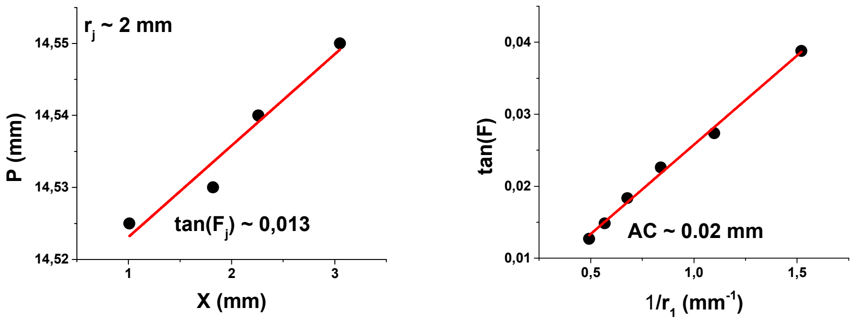

Figure 7. Experimental determination of the PFT angle F_j for a beam size r_j: Position of the interference line X vs. position P of the interferometer mirror (left) and quantity AC relating $\tan(F_j)$ and $(1/r_j)$ for grating G1 (33l/mm; right).

In applying the described procedure, we used two different diffraction gratings G1 (33l/mm) and G2 (160l/mm).

As an example, in the left graph in Figure 7 we show the dependence of the half of the delay between the interfering pulses P (given by the position of the interferometer mirror) on the position X of the interference line with maximal contrast for a beam size at the CCD camera sensor $r_j = 2$ mm. Here we keep the notations introduced in Figure 4. From a series of such measurements for different beam sizes r_j on the CCD camera (at different camera locations) we get the dependence shown in the right graph in Figure 7. For each of the two diffraction gratings we determined the quantity AC:

$$AC = 0.020(\pm 0.001) \text{ mm for grating G1 } (33l/\text{mm})$$

and

$$AC = 0.21(\pm 0.01) \text{ mm for grating G2 } (160l/\text{mm}).$$

In order to confirm the correctness of these values we calculated back (see Eq. 2) the PFT angle for a beam size at a position, at which we already measured the PFT angle in an independent experiment. In this preceding experiment we used the same inverted field interferometer as a part of an inverted field SHG correlator. It is fair to say that the comparison between these values is good (see Table 1).

Table 1. Comparison between the values for the PFT angle F obtained by an inverted field SHG autocorrelator and by an inverted field interferometer as described in this work.

	Grating G1	Grating G2
Beam size	63 μm	130 μm
PFT angle F measured in an independent experiment	13°	57°
PFT angle F obtained in this work	17°	58°

6 Conclusion

The described experimental procedure and the results confirm that the approach to determine the relation between the laser beam size and the pulse front tilt angle of ultrashort pulses by using an inverted field interferometer is easy to apply and of high fidelity. These results seem to be a useful criterion for the precision in aligning (in principle) dispersionless systems for manipulating ultrashort pulses, as well as in cases when the pulse front tilt is a result of a desired spatio-temporal coupling. Further experiments should be focused on evaluating possible limitations in the applicability of this method.

Acknowledgments

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