Wavefront-tilt Correction of Laser Pulses by Dispersion Management

Samuel Buck, Marco Galimberti
Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, UK
Contact: samuel.buck@stfc.ac.uk

Abstract

A new diagnostic has been tested to visualise pulse-front-tilt in ultrashort laser pulses. Dispersive mediums (4° glass prisms) were rotationally controlled about the beam axis in accordance to the diagnostic, via an automated loop, to successfully minimise existing angular dispersion from a commercial oscillator output.

1 Introduction

Ultrashort pulse laser science faces a plethora of challenges in maintaining and measuring high-quality pulses. This is due to the time-bandwidth-product (TBP), which, for femtosecond lasers, necessitates a very broad (typically >100 nm) optical bandwidth [1]. Dispersive properties of optics become quickly detrimental over such large bandwidths, compelling careful control and diagnosis of short pulse lasers [2]. One common complication is angular dispersion (AD) - where the transmission through optical mediums in the laser chain cause divergence between longer and shorter wavelengths, i.e. chromatic aberration [3]. This is most regularly caused by: imperfect alignment of the stretcher and compressor in chirped pulse amplification laser systems [4, 5], and transmission through wedged windows (required to mitigate back reflections).

The presence of AD has been shown to lead to what is known as a pulse-front-tilt (PFT) [6]: the laser pulse front lies at an angle to its direction of propagation, resulting in sub-optimal experimental applications; ideally the laser pulse PFT is minimised such that the intensity on target is maximised. More specifically, it has been reported that the presence of PFT in high powered laser systems causes a wakefield asymmetry which leads to a deflection of the electron beam [7].

2 Compensation

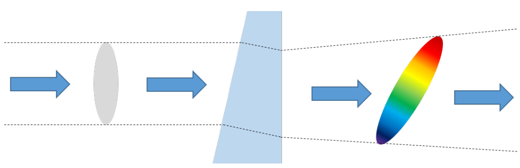

Figure 1: A broadband laser pulse incident onto a wedged optic will introduce angular dispersion giving a pulse-front tilt.

Figure 1 simplistically demonstrates how wedged optics will induce angular dispersion to a pulse. This can quickly be seen analytically after applying Snell's Law and the small angle approximation for the input $\theta_{in}(\lambda)$ and output $\theta_{out}(\lambda)$ angles to a pulse's deviation from the beam axis - normal to the flat surface of the prism(s), harboring refractive index $n(\lambda)$ and wedge angle α: $\theta_{out}(\lambda) = n(\lambda)\alpha - \theta_{in}(\lambda)$. This compounds to any number of prisms to give a more general description:

$$\theta_{out}(\lambda) = \sum n_i(\lambda)\alpha_i - \theta_{in}(\lambda) \tag{1}$$

Henceforth in this report, we will approximate linear AD presence ($\frac{d\theta}{d\lambda} = constant$), such that 2 prisms of the same glass can be tuned to completely compensate/remove it.

T extend the problem to 2-dimensions, we can introduce the rotation matrix $R(\theta_{z_i})$ (where θ_{z_i} is the rotation about the z-axis for prism i) to visualise the pulse's dispersion in both x & y axes:

$$\vec{\theta}_{out}(\lambda) = (R(\theta_{z_1}) + R(\theta_{z_2})) \begin{pmatrix} n(\lambda)\alpha \\ 0 \end{pmatrix} \tag{2}$$

where a comparatively negligible input angle has been assumed. Expanding the rotation matrix and applying trigonometric identities to the above, we find:

$$\vec{\theta}_{out}(\lambda) = 2\cos\left(\frac{\theta_{z_1} - \theta_{z_2}}{2}\right) \begin{pmatrix} \cos\left(\frac{\theta_{z_1}+\theta_{z_2}}{2}\right) & -\sin\left(\frac{\theta_{z_1}+\theta_{z_2}}{2}\right) \\ \sin\left(\frac{\theta_{z_1}+\theta_{z_2}}{2}\right) & \cos\left(\frac{\theta_{z_1}+\theta_{z_2}}{2}\right) \end{pmatrix} \begin{pmatrix} n(\lambda)\alpha \\ 0 \end{pmatrix} \tag{3}$$

It is, henceforth, useful to visualise the prism rotations compared to the undeviated configuration ($\theta_{z_1} = 0, \theta_{z_2} = \pi$ and thus we will substitute $\theta'_{z_2} = \theta_{z_2} + \pi$. Then, taking the magnitude $\mid \vec{\theta}_{out}(\lambda) \mid$ and argument $arg(\vec{\theta}_{out}(\lambda))$ of eq (3) shows dependencies on the difference and sum of the prism rotations respectively:

$$\mid \vec{\theta}_{out}(\lambda) \mid = 2n(\lambda)\alpha \sin^{-1}\left(\frac{\theta_{z_1} - \theta'_{z_2}}{2}\right) \tag{4}$$

$$arg(\vec{\theta}_{out}(\lambda)) = \frac{\theta_{z_1} + \theta'_{z_2} - \pi}{2} \tag{5}$$

3 Measurement & Optimisation

Current diagnostics for quantifying PFT usually require complex setups involving cross correlation devices which are non-trivial to align and maintain, costly, and self-referenced [8, 9, 10]. A common and simple practice to search for PFT in laser systems is to focus the beam using an appropriate lens and observe at the focal plane with a camera: if the image comprises of a neat, symmetrical, airy disk focus, it can be deduced there is no prevalent angular dispersion. If, however, the focus is more of a line, then there could be either PFT or astigmatism present in the beam. For high repetition-rate lasers, it can be easily assured whether or not astigmatism is present - leaving a diagnostic for PFT only. For high energy (and therefore lower repetition rate) laser systems, this is not feasible.

A new diagnostic developed by Galimberti et al provides a fast and simple method of visualising PFT by diffracting the beam and evaluating the far-field [11]. Specifically, a polka-dot beamsplitter acts as a diffraction grating in the horizontal and vertical axes of the beam to form diffracted copies of the beam, which, when focused onto a camera, reveals distinct lines as illustrated in Figure 2. The angles of these foci describe the AD present in the laser pulse and can be quantified with some basic image analysis.

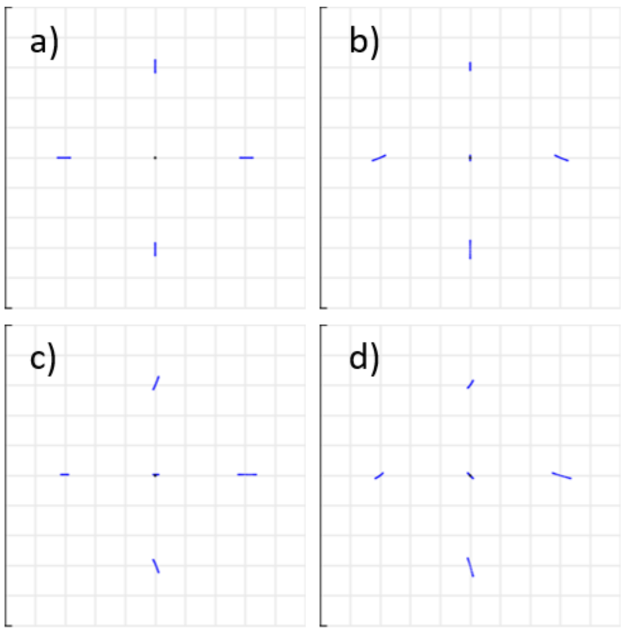

Figure 2: Example diagnostic images obtained from Opticstudio: a) No angular dispersion (AD); b) Linear AD in y; c) Linear AD in x; d) Linear AD in both axes.

To create an automatic optimisation loop, the diffracted foci can be interpolated into straight lines. The angles from these lines correspond to the dispersion in x & y axes and are converted to polar coordinates, which from eqs 4 & 5, relate to the required prism rotations with which to counteract/remove the existing AD. A simple feedback algorithm then provides step sizes for the prisms rotations until a given threshold for the PFT is met.

The described method was tested on a commercial Venteon oscillator outputting pulses of 6 fs in duration which are stretched by a double-pass N-BK7 glass stretcher to about 3 ps.

Thorlabs N-BK7 round wedge prisms with 4 $^\circ$ beam deviation were mounted in motorised precision stages. These motors were controlled by LabVIEW through K-cube motor controllers. A 1 " fused silica polka-dot beamsplitter was used as the diffraction element. An iDS uEye+ cam-era was used to record the incident beam profile directly to LabVIEW. A schematic layout of the experimental setup is shown in Figure 3.

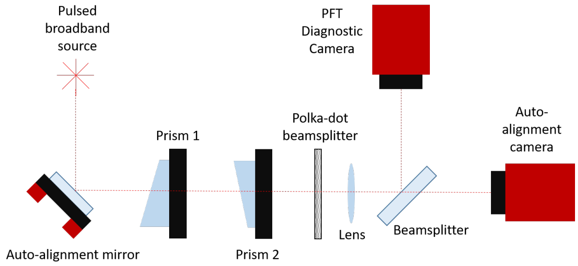

Figure 3: Schematic layout of the experimental setup: a broadband pulse from a commercial oscillator is directed by an automatic alignment loop through two 4°prisms, a polka-dot beamsplitter and a focusing lens.

Figure 4: AD diagnostic camera images of undeviated (left) and optimised (right) pulse.

Figure 4 shows the camera image before and after optimisation: the initial, undeviated ($\theta_{z_1} = 0°$, $\theta_{z_2} = 180°$) pulse from the oscillator shows mostly vertical AD; after the optimisation loop has been performed the diffracted wings have flattened, indicating a successful compensation at the new prism angles at $\theta_{z_1} = 39°$, $\theta_{z_2} = 232°$.

4 Conclusion & Discussion

A new diagnostic has been tested to evaluate the presence of angular dispersion within ultrashort laser pulses. The results from the diagnostic were used in an automated loop to direct rotational-motorised wedged optics to induce intentional linear dispersion in order to compensate the existing angular dispersion and hence minimise the pulse front tilt.

The study will continue to the case of 4 wedges, in 2 pairs of glasses, in order to accommodate a broader and more complicated spectral bandwidth/dispersion.

The successful demonstration of this setup will lead to implementation on the VOPPEL and EPAC short pulse beamlines as a way of providing control and optimisation of the pulse to the users.

References

[1] Siegman, A. E. (1986). Lasers. Taiwan: University Science Books.

[2] Hecht, E. (2017). Optics. United Kingdom: Pearson Education, Incorporated.

[3] Akturk, S., Gu, X., Zeek, E., & Trebino, R. (2004). Pulse-front tilt caused by spatial and temporal chirp. Optics Express, 12(19), 4399. https://doi.org/10.1364/opex.12.004399

[4] Strickland, D., & Mourou, G. (1985). Compression of amplified chirped optical pulses. Optics Communications, 55(6), 447–449.

[5] Osvay, K., Kovacs, A. P., Heiner, Z., Kurdi, G., Klebniczki, J., & Csatari, M. (2004). Angular Dispersion and Temporal Change of Femtosecond Pulses From Misaligned Pulse Compressors. IEEE Journal of Selected Topics in Quantum Electronics, 10(1), 213–220.

[6] J. Hebling, “Derivation of the pulse front tilt caused by angular dispersion”, Opt. Quantum Electron. 28 (12), 1759 (1996), doi:10.1007/BF00698541

[7] Thévenet, M., Mittelberger, D. E., Nakamura, K., Lehe, R., Schroeder, C. B., Vay, J.-L., Esarey, E., & Leemans, W. P. (2019). Pulse front tilt steering in laser plasma accelerators. Physical Review Accelerators and Beams, 22(7).

[8] Figueira, G., Braga, L., Ahmed, S., Boyle, A., Galimberti, M., Galletti, M., & Oliveira, P. (2019). Simultaneous measurement of pulse front tilt and pulse duration with a double trace autocorrelator. Journal of the Optical Society of America B, 36(2), 366.

[9] Jean-Baptiste, M., Zhao, C., Rodrigo, L.-M., & Thomas, O. (2020). Single-shot diagnosing of spatiotemporal couplings in ultrashort laser pulses by spatiospectral imaging of a third-order nonlinear process. Optics Letters, 45(8), 2207.

[10] Akturk, S., Kimmel, M., O’Shea, P., & Trebino, R. (2003). Measuring pulse-front tilt in ultrashort pulses using GRENOUILLE. Optics Express, 11(5), 491.

[11] M. Galimberti, F.G. Bisesto, and M. Galletti. Innovative single-shot 2D pulse front tilt diagnostic. Article submitted to: High Power Laser Science and Engineering, (2020)