Research Article

Lasse Büsing*, Tobias Bonhoff, Lars Behnke, Jochen Stollenwerk and Peter Loosen

# Theoretical and experimental analysis of scan angle-depending pulse front tilt in optical systems for laser scanners

DOI 10.1515/aot-2015-0046
Received October 22, 2015; accepted November 30, 2015; previously published online January 8, 2016

**Abstract:** For realising fast and highly dynamical laser-based material processing, scanner systems are already utilised for many different industrial applications. Furthermore, ultra-short pulsed (<1 ps) laser sources provide possibilities of processing most different materials with highest accuracy. Owing to the large spectral bandwidth of ultra-short laser pulses, dispersion in optical components becomes relevant. The dispersion in optical systems for laser scanners may lead to scan angle-depending pulse properties as, for example, pulse front tilt. The investigation of these effects is not state of the art today but absolutely necessary to exploit the full potential of laser scanners for ultra-short pulse applications. By means of an exemplary focusing lens, the simulation and experimental analysis of scan angle-depending pulse front tilt is presented for the first time.

**Keywords:** dispersion; material processing; pulse front tilt; scanner system; ultra-short pulse.

## 1 Introduction

Many applications of material processing with ultra-short pulses react very sensitively on changes of the pulse properties. A tilted pulse front, for example, may lead to significant changes of the light matter interaction especially when processing transparent dielectrics. Depending on the feed direction, a pulse front tilt (PFT) may cause significant changes of the processing results [1]. Furthermore, the focal pulse duration will be extended due to the PFT, which results in a decrease in the maximum pulse intensity [1–4]. A PFT is induced by dispersive optical elements such as prisms, gratings, or lenses, which are passed through non-axially, i.e. at a field angle [5].

For the processing of large areas, laser scanner systems are an established tool allowing high process speed and highly dynamical applications. The utilization of a focusing lens as, for example, an f-$\theta$ lens behind the deflection system is a proven method and already used in many industrial manufacturing systems. The beam path through the focusing lens changes depending on the scan angle (Figure 1). The application of these scanner systems for ultra-short laser pulses, therefore, may lead to scan angle-depending pulse properties and, thus, position-dependent processing results.

Even though the propagation time difference (PTD) between pulse and phase front already has been investigated in detail for single lenses and axially parallel incidence of light [6], the investigation of scan angle-depending PFT is not state of the art today. To our knowledge, we present for the first time experimental investigations of this effect as well as a detailed comparison with simulation results. Therefore, two different simulation methods are taken into account, which are based on geometrical optics, on the one hand, and wave optics, on the other hand. For the experimental investigations, the scan angle-dependent PFT is measured using a single-shot autocorrelator.

## 2 Simulation

### 2.1 Fundamentals

In dispersive materials with refractive index $n(\lambda)$, a PTD appears as the propagation velocities of the phase front

***Corresponding author: Lasse Büsing,** RWTH Aachen University – Chair for Technology of Optical Systems (TOS), Steinbachstr. 15, Aachen 52074, Germany, e-mail: lasse.buesing@tos.rwth-aachen.de
**Tobias Bonhoff and Lars Behnke:** RWTH Aachen University – Chair for Technology of Optical Systems (TOS), Aachen, Germany
**Jochen Stollenwerk and Peter Loosen:** RWTH Aachen University – Chair for Technology of Optical Systems (TOS), Aachen, Germany; and Fraunhofer – Institute for Laser Technology (ILT), Aachen, Germany

**www.degruyter.com/aot**

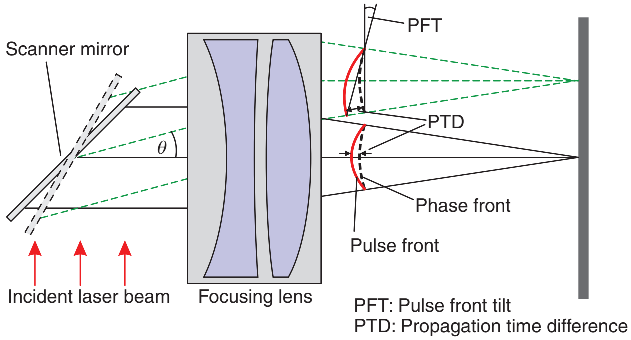


**Figure 1:** Principles of pulse deformations induced by a laser scanner system [5].

and the pulse front are different. The PTD can be calculated using

$$\mathrm{PTD}=\frac{l}{c}\left(-\lambda\frac{dn}{d\lambda}\right) \quad (1)$$

where $l$ is the path length in the dispersive material and $c$ the speed of light in a vacuum [6]. For normal dispersion, the PTD is positive, and therefore, the pulse front is delayed with respect to the phase front. A PTD, which is asymmetric around the chief ray, is also called PFT. With the normalised pupil coordinate $\rho$, we define the PFT as the difference between the PTD for the marginal rays

$$\mathrm{PFT}=\mathrm{PTD}(\rho=-1)-\mathrm{PTD}(\rho=1) \quad (2)$$

Therefore, the PFT is invariant with respect to the z-position in a focused beam. This is a useful property regarding the investigation of ultra-short pulses in the laser beam behind a focusing lens. Often, the PFT is considered as PTD difference per millimetre beam diameter [2, 7]. In this case, the PFT would strongly depend on the position of the detector plane in the focused beam. For this reason, equation (2) is considered to specify the PFT. Following a geometrical and a wave optical approach, PTD and PFT are simulated behind the focusing lens. Both approaches are explained in the following.

## 2.2 Geometrical optics

For a single ray, the PTD induced by one optical element can be determined using equation (1). To calculate the PTD for an optical system, which consists of multiple elements, the PTDs for all elements are summed. Therefore, the path lengths $l_i$ for this ray in every optical element $i$ are calculated by ray tracing using Zemax (Figure 2).

The index of refraction $n(\lambda)$ is given by the Sellmeier model for several materials in the glass catalogue of the ray-tracing software. The derivative of $n$ with respect to $\lambda$

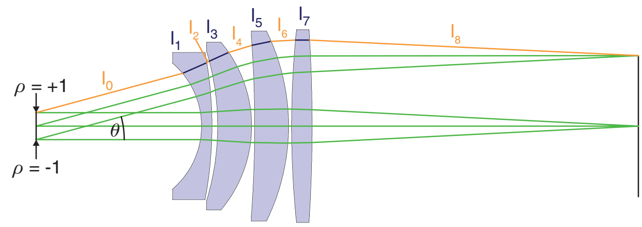


**Figure 2:** Illustration of the ray-tracing approach to calculate the PTD.

is calculated and inserted into equation (1). In this way, the PTD can be determined for a bundle of rays and can be simulated either as a cross section through the whole beam or as a two-dimensional surface. For all calculations presented in chapter 4, a set of 50 rays is homogeneously distributed in the scan direction along the entrance pupil to calculate a cross section of the PTD.

## 2.3 Wave optics

For the wave optical analysis, a bandwidth-limited pulse with Gaussian temporal pulse shape is modelled as a set of $N_\lambda$ wavelengths. Using the software tool VirtualLab Advanced (Version 5.11.0), the pulse is propagated through the optical system. In the observation plane, for each wavelength, the vectorial field components are calculated. The approach for calculating the PTD and the PFT is depicted in Figure 3.

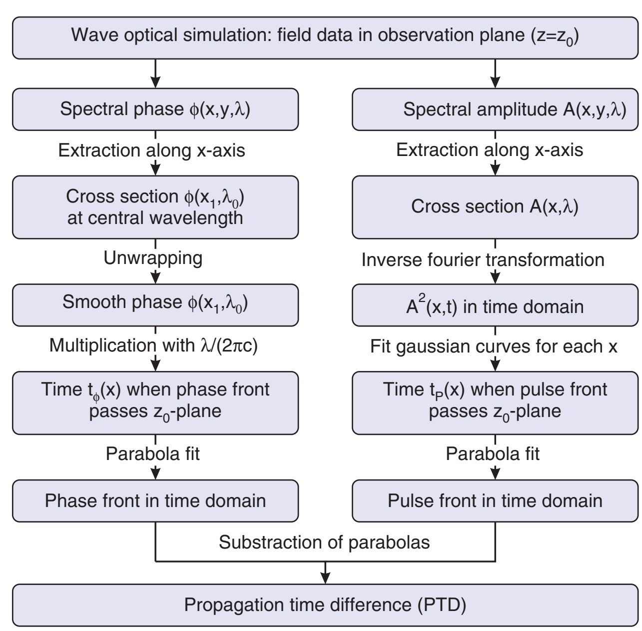


**Figure 3:** Flow chart of the PTD calculation for the wave optical approach [5].

A cross section of the spectral phase $\phi(x,y=0,\lambda_0)$ at the centre wavelength is extracted and unwrapped. A multiplication of $\phi(x,\lambda_0)$ with $\lambda_0/(2\pi c)$ yields the time $t_\phi(x)$ when the phase front passes the observation plane. The spectral amplitude $A(x,y,\lambda)$ is extracted along the same cross section as the spectral phase. Utilizing an inverse Fourier transformation, the squared field amplitude $A^2(x,t)$ in the time domain can be calculated. For each $x$, a Gaussian-shaped curve is fitted to the squared field amplitude to identify the centre of the pulse $t_p(x)$. The pulse front passes the observation plane at the time $t_p(x)$. Hence, the PTD can be calculated as the difference between the times $t_\phi(x)$ and $t_p(x)$ [5].

## 2.4 Design of an exemplary focusing lens

For an exemplary test case, a telecentric focusing lens is designed for a wavelength of 800 nm. The lens system enables diffraction-limited focusing for field angles up to 6° and a beam diameter of 5 mm ($1/e^2$). The system's focal length is 68 mm, and the numerical aperture is 0.037. The design is depicted in Figure 4. To facilitate a comparison between the measured and the simulated PFT, the focusing lens is designed with a relatively large scan angle-dependent PFT. At a scan angle of 1°, the PFT is about 10 fs, which corresponds to 2 fs/mm directly behind the focusing lens. Typical PFT values for ultra-short pulse experiments are in the range of 1–2 fs/mm as well, measured in the collimated beam [2]. In particular, a chromatic correction is renounced, and the system is optimized only for the centre wavelength of the laser.

# 3 Experimental setup

For the experimental investigation of the scan angle-dependent PFT, a rotatable mirror is mounted in the entrance pupil of the focusing lens. By using a second identical lens, the beam is collimated again and coupled into a single-shot autocorrelator (TiPA, light conversion). The collimating lens, as well as the autocorrelator, is mounted on a movable stage (Figure 5).

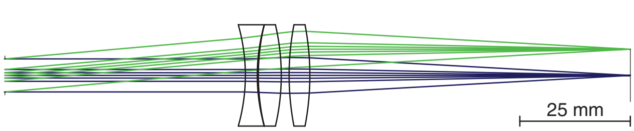


**Figure 4:** Design of the telecentric focusing lens for exemplary investigations of a scan angle-dependent PFT.

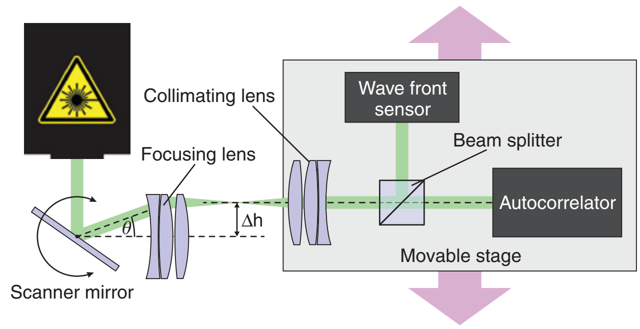


**Figure 5:** Sketch of the measurement setup for investigating the scan angle-dependent PFT by using a single-shot autocorrelator and a wave front sensor.

For each scan angle, the position of the stage is adjusted in a way that the beam passes centrically through the collimating lens. In this way, the collimating lens induces a rotational symmetric PTD and, hence, does not contribute to the PFT. Furthermore, the beam direction behind the collimating lens is constant as the lens systems are designed telecentrically. A precise positioning of the stage is realised by integrating a wave front sensor in the beam path behind the collimating lens.

As laser source, a Libra-F-1k-230 from Coherent is used, which provides pulses with a duration of 130 fs at a wavelength of 800 nm. The corresponding spectral bandwidth is about 15 nm. The scan angle-dependent PFT is investigated in the range of $-6° < \theta < 6°$ in steps of 2°.

# 4 Comparison of results

For different scan angles $\theta$, the PTD is calculated directly behind the lens system using both the ray tracing and the wave optics approach. In Figure 6, the results are illustrated as a function of the normalised pupil coordinate $\rho$.

Both theoretical approaches show a high degree of accordance with differences <2 fs. Therefore, the geometrical analysis is assumed to be appropriate for further investigations. Nevertheless, the validity in the vicinity of the focus has to be examined separately. The experimental investigation of the PFT requires an additional collimating lens, which is shifted laterally with respect to the focusing lens depending on the scan angle. The impact of the collimating lens on the PTD is investigated utilising the ray-tracing approach. For different scan angles, the PTD behind the focusing lens and behind the collimating lens are depicted in Figure 7 as a function of the pupil coordinate.

The simulation results show stronger bended PTDs behind the collimating lens. This is plausible because

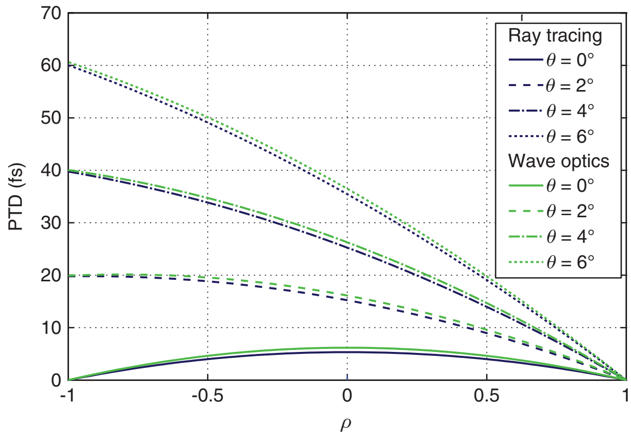


**Figure 6:** PTD for different scan angles directly behind the lens system calculated by ray tracing and wave optical analysis as a function of the pupil coordinate.

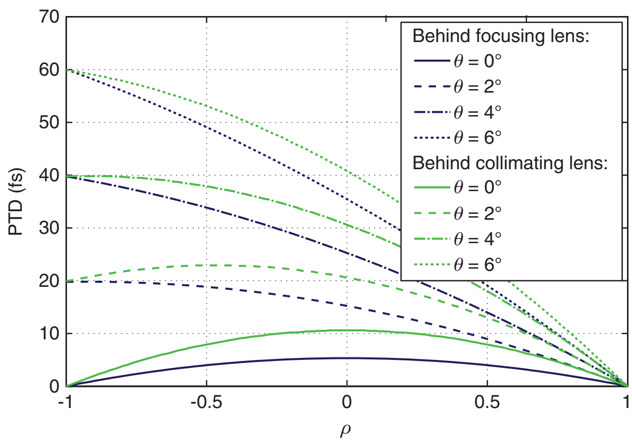


**Figure 7:** PTD as a function of the pupil coordinate for different scan angles behind the focusing lens and behind the collimating lens calculated by ray tracing.

the PTD of both focusing and collimating lens have to be considered in this case. Owing to the telecentricity of the focusing lens, the beam passes axially through the collimating lens for all investigated scan angles. Therefore, the PFT is not affected by the collimating lens as the PFT is determined only by the PTD at $\rho$=-1 and $\rho$=1. The scan angle-dependent PFT is measured three times to estimate the measurement inaccuracies. The averages and inaccuracies of the measurement results as well as the simulation by ray tracing are depicted in Figure 8.

Both simulation and measurement of the PFT show a linear dependency of the scan angle $\theta$. By means of a linear regression, the slope of 9.9 fs/° is retrieved for the ray-tracing data. However, the regression line for the measurement data is shifted -30 fs with respect to the simulation and shows a slope of 12.1 fs/°. Possible reasons for a shift of the measurement data can be an initial PFT of the incident laser pulse or tolerances of mechanical and optical components as well as misalignment of the autocorrelator. Tolerances of the lens system may also affect the slope and are further investigated by performing a Monte Carlo simulation. Therefore, 1000 systems are simulated with randomized deviations for all optical components within estimated tolerances. This calculation yields a standard deviation of the slope of ±0.8 fs/°.

In addition, the measurement approach, itself, leads to further uncertainties. To obtain PFT values from the measured detector signal, a calibration factor is required. This calibration factor can be achieved with a calibration method provided by the manufacturer. During the calibration, a dependency of the calibration factor on the pulse duration and the initial PFT is observed. This dependency does not agree with the manufacturer information and leads to uncertainties of the measured absolute values. Deviations

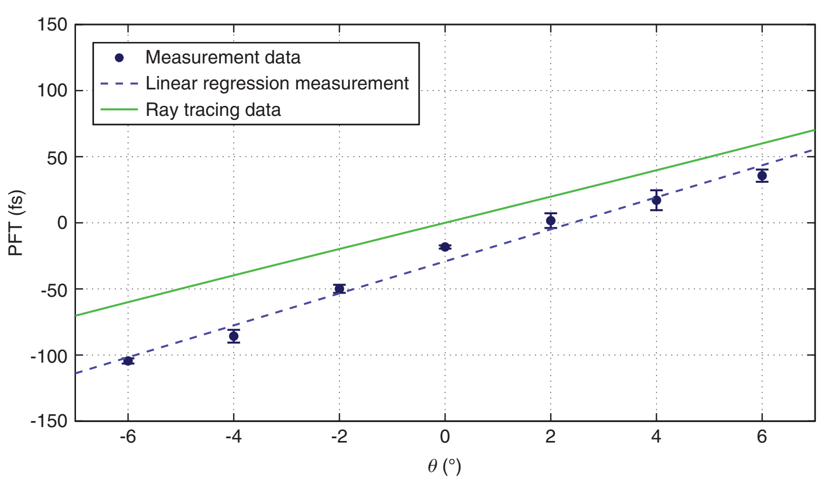


**Figure 8:** Measurement and simulation results of the scan angle-depending PFT.

of the calibration factor will lead to systematic deviations of the following measurements and, therefore, affect the slope of the scan angle-depending PFT. Furthermore, the autocorrelator enables the PFT measurement in only one dimension. An initial PFT in the other dimension cannot be measured but will influence the results. Influences of these effects are currently under investigation. The first estimations show systematic deviations of about 3% (0.4 fs/°).

## 5 Conclusion

Both theoretical approaches provide consistent results for the pulse shape behind the optical system and show a linear increasing PFT for ascending scan angles. The same relation can be seen in the results of the experimental investigation. Through quantitative data evaluation, deviations of approximately 20% are calculated between simulation and measurement. A tolerance analysis of the optical system leads to an uncertainty of almost ±10% for the experimental investigation. Alignment and calibration of the autocorrelator are expected to cause further uncertainties, which are still under investigation. Therefore, the experimental results are considered to be concordant with the simulation within the scope of the uncertainties.

Future research might lead to improvements of the measurement technology as, for example, the consideration of PFT in two dimensions simultaneously. To enhance material processing with ultra-short pulses by utilizing laser scanners, methods for compensating the scan angle-depending PFT as, for example, achromatic lenses will be investigated.

**Acknowledgments:** The authors would like to thank the German Research Foundation (DFG) for its support within the project 'LO 640/12-1' at RWTH Aachen University.

## References

[1] P. G. Kazansky, W. Yang, E. Bricchi, J. Bovatsek, A. Arai, et al., Appl. Phys. Lett. 90, 151120–151123 (2007).
[2] P. G. Kazansky, Y. Shimotsuma, M. Sakakura, M. Beresna, M. Ius, et al., Opt. Express 19, 20657–20664 (2011).
[3] J. Gottmann, JLMN 8, 15–18 (2013).
[4] W. Yang, P. G. Kazansky, Y. Shimotsuma, M. Sakakura, K. Miura, et al., Appl. Phys. Lett. 93, 171109–171103 (2008).
[5] L. Büsing, T. Bonhoff, J. Gottmann, P. Loosen, Opt. Express 21, 24475 (2013).
[6] Z. Bor, Opt. Lett. 14, 119–121 (1989).
[7] S. Akturk, M. Kimmel, P. O'Shea, R. Trebino, Opt. Express 11, 491–501 (2003).

**Lasse Büsing**
RWTH Aachen University – Chair for Technology of Optical Systems (TOS)
Steinbachstr. 15 Aachen 52074, Germany
**lasse.buesing@tos.rwth-aachen.de**

Lasse Büsing received his Master of Science in Physics at the RWTH Aachen University in 2011. He specialized in lasers and optics during his stay at the KTH in Stockholm 2010 and wrote his Master's thesis at the Fraunhofer-Institute for Laser Technology in Aachen. As scientific employee he started working at the Chair for Technology of Optical Systems (TOS) at the RWTH Aachen University. His research activities are concentrated on optical system design for ultra-short pulse laser applications. In 2014 he became head of the group 'Optical Systems' at the TOS where he is dealing with advanced optical systems for different laser applications.

**Tobias Bonhoff**
RWTH Aachen University – Chair for Technology of Optical Systems (TOS)
Aachen, Germany

Tobias Bonhoff is research assistant at the Chair for Technology of Optical Systems at RWTH Aachen University, Germany. He studied Physics and received his MSc degree from the RWTH Aachen University in 2014. During his Master studies, he passed an internship in the field of laser material processing at the Townes Laser Institute, University of Central Florida. His current research focuses on thermo-optical effects in high power laser optics and on dispersive effects of ultra-short pulses.

**Lars Behnke**
RWTH Aachen University – Chair for Technology of Optical Systems (TOS)
Aachen, Germany

Lars Behnke is a student research assistant at the RWTH Aachen University and works at the chair for technology of optical systems. He studies Physics at RWTH Aachen University. In 2015, he wrote his Bachelor thesis about scan angle-dependent deformation of ultra-short laser pulses caused by focusing optics.

**Jochen Stollenwerk**
RWTH Aachen University – Chair for Technology of Optical Systems (TOS) Aachen, Germany; and Fraunhofer – Institute for Laser Technology (ILT), Aachen, Germany

Jochen Stollenwerk received his Diploma degree in Physics at the RWTH Aachen University in 1996. He was a scientific employee at the Fraunhofer Institute for Laser Technology (ILT) and received his PhD in the area of laser material processing in 2001. In the same year he became Manager Application at TRUMPF Laser Marking Systems, Grüsch, Switzerland. In 2004 he became Vice Director at the newly founded Chair for the Technology of Optical Systems at RWTH Aachen University and Head of the Research Group 'Thin Film Laser Processing' at the ILT. The research and teaching activities of Jochen Stollenwerk are concentrated on advanced optical systems for laser and laser systems as well as for lighting applications, EUV technology and on laser material processing.

**Peter Loosen**
RWTH Aachen University – Chair for Technology of Optical Systems (TOS) Aachen, Germany; and Fraunhofer – Institute for Laser Technology (ILT), Aachen, Germany

Peter Loosen received his Diploma degree at the Technical University of Darmstadt in the field of lasers for industrial manufacturing in 1980. He was a scientific employee at the Institute of Applied Physics of the Technical University of Darmstadt and received his PhD in the working group of Professor Herziger in the area of 'High-Power CO2-Laser with Axial Gas Flow' in 1984. After his PhD-examination he moved to the newly founded Fraunhofer-Institute for Laser Technology in Aachen (ILT) in 1985, where he was responsible for the department 'Gas Laser'. In 1989 he additionally took over the responsibility for the departments Solid-state Lasers, Metrology and Plasma Systems of the Fraunhofer-Institute. Since 1993 he has been the deputy head of the ILT and was appointed the Professor for 'Technology of Optical Systems' and head of the newly formed respective institute at the RWTH-Aachen in 2004. The research and teaching activities of Peter Loosen are concentrated on the fundamentals and the technology of lasers and laser systems for industrial manufacturing and on optical systems for laser and laser systems. He has made considerable contributions in the fields of industrial high-power gas-, solid-state and diode lasers and the integration of such lasers into production applications.