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HIGH-ENERGY SINGLE-CYCLE TERAHERTZ SOURCES FOR COMPACT PARTICLE ACCELERATORS AND MANIPULATORS

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Abstract

Terahertz-driven (THz) accelerators and manipulators promise to yield short femtosecond electron bunches of high brightness with intrinsic synchronization to the driving laser at a compact and economic footprint. However, development of practical devices requires THz sources that reliably provide pulse energies in the sub-mJ to mJ regime, which in turn require state-of-the-art pump laser systems and carefully designed optical transport lines. Here, we investigate both by experiments and simulations on how spatio-temporal coupling of pump pulse parameters in tilted-pulse-front based terahertz setups can be used to control the position of the "temporal focus", which is where minimum pump pulse duration is reached. This concept opens a pathway to pump tilted-pulse-front setups with arbitrarily stretched pulses which significantly simplifies transport lines for lasers with high peak intensity. This concept is experimentally demonstrated by efficiently pumping a tilted-pulse-front THz source with pulses stretched to 10 ps and extraction of a THz energy of 0.4 mJ while operating well-below damage threshold. Our findings are not just relevant for THz based particle acceleration and strong-field physics but any application that requires control over the temporal focus of beams with a tilted-pulse-front such as other novel laser-based particle accelerator schemes.

INTRODUCTION

Terahertz-driven ("THz") accelerators [1-5] and manipulators [5-8] promise to yield short femtosecond electron bunches of high brightness with intrinsic synchronization to the driving laser at a compact and economic footprint. However, no THz-driven accelerator has reached the performance required for practical applications yet. Besides challenges associated with the physical miniaturization, the lack of efficient, high-energy single-cycle THz sources is one of the key challenges to overcome for the realization of practical THz accelerators. Single-cycle THz pulses in the required frequency band between 0.1 - 0.5 THz are commonly generated by optical rectification of ultrafast laser pulses in lithium niobate using pump pulses with a tilted intensity-front [9]. However, there remains a deficit of experimental studies comprehensively mapping out the dependence of the performance on key setup and pump pulse parameters. As a result, certain questions about the physics of the non-collinear interaction remain unanswered. This prevents rigorous development of the setups beyond the state of proof-of-principle experiments [10, 11] to where setups reliably provide the high pulse energies required for practical accelerators and beam manipulators on a day-to-day basis.

Following up on our recent experimental study on the parameter sensitivities in tilted-pulse-front setups [12], here we investigate both by experiments and simulations how spatio-temporal coupling of the pump pulse parameters affects the setup performance. In particular, we investigate the effect of pump pulse group-delay dispersion (GDD_0) on the THz conversion since stretched pump pulses circumvent self-focusing and can conveniently be propagated over long distances. This requires considering the interdependence of pump pulse chirp and the propagation coordinate z arising for pulses with spatio-temporal distortions such as pulse-front tilt. This spatio-temporal coupling is a key factor because it leads to a minimum in the pump pulse duration ("temporal focus"), unaffected in magnitude but shifting along z if GDD_0 is altered. This phenomenon is investigated both experimentally and numerically and, based on the findings, control of the temporal focus is experimentally demonstrated. Finally, this concept is applied to demonstrate efficient operation of a tilted-pulse-front THz setups with highly chirped (1.44 ps^2, corresponding to a stretching factor of 25) pump pulses, yielding 0.4 mJ of usable THz pulse energy.

Conclusively, this concept opens a novel pathway to operate tilted-pulse-front setups with arbitrarily stretched pump pulses, which significantly simplifies the beam transport line of lasers with high peak intensity, but also allows to fine-tune the spatio-temporal pump pulse parameters at a given target point. Therefore, our findings are not only relevant for THz based particle acceleration but for any tilted-pulse-front based application, where either control of the temporal focus is required or where pump pulses with high peak intensities are used, such as dielectric or laser-plasma accelerators [13, 14].

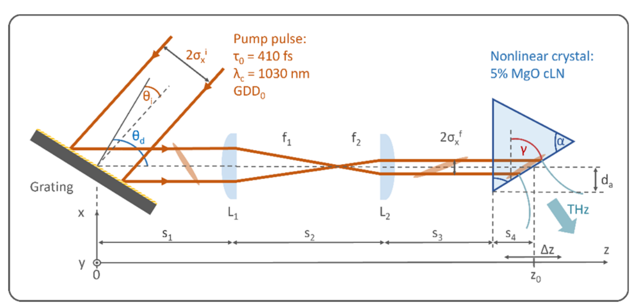

Figure 1: Schematic drawing of the setup including crucial tuning parameters.

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RESULTS

Experimental Setup

The tilted-pulse-front setup schematically shown in Fig. 1 was pumped by a commercially available Yb-based amplifier system providing 410 fs pump pulses up to 200 mJ energy centered at $\lambda = 1030$ nm and repetition rate of 52 Hz [15]. The THz setup was designed and optimized based on the considerations and procedures laid out in Ref. [12]. The congruent 5 % MgO:LiNbO3 prism ("cLN", $\alpha = 62°$, 35 mm tall) was cryogenically cooled to 82 K using liquid nitrogen. A reflective diffraction grating ($\rho = 1500$ l/mm, diffraction order $m = 1$) paired with a cylindrical telescope ($M = 0.654 \pm 0.002$) was used to tilt the intensity front of the pump pulse and image the grating.

The initial GDD on the pump pulse (GDD_0) was controlled by tuning of the optical path between the diffraction gratings in the optical compressor of the laser system, while the crystal was positioned along the z-axis by use of a motorized translation stage. All THz pulse energies reported in this work refer to the usable energy measured outside of the dewar, corrected by the measured average transmission (≈ 54 %) through the black polyethylene cover (1.9 mm thickness) in front of the calibrated THz detector (THz 20, SLT Sensor- und Lasertechnik GmbH).

Numerical Simulations

Numerical calculations based on the 4x4 matrix formalism developed by Kostenbauder [16] were performed to study the evolution of crucial pump pulse parameters such as pulse-front tilt γ and pulse duration τ (FWHM intensity) as a function of z, grating angle θ_d, and initial pump pulse chirp (GDD_0). Figure 2 shows the simulated evolution of pulse duration τ and pulse-front-tilt γ vs. the relative longitudinal crystal coordinate Δz. Computations were performed for $GDD_0 = 0$ and θ_d^{opt} as well as for pulses stretched by a factor of x25 and detuned θ_d by ±1°. Note, $\Delta z = z - z_0 = 0$ marks the position at which $\tau = \tau_{min}$ ("temporal focus") for $GDD_0 = 0$.

Figure 2a shows that for $GDD_0 = 0$ the position of the temporal focus is independent of θ_d. However, the temporal focus is shifted along z if chirp (GDD_0) is applied to the pump pulse before it enters the tilted-pulse-front setup according to:

$$\Delta z = \frac{2\pi c^2 M^2}{\lambda^3}\left(\frac{m\rho}{\cos\theta_d}\right)^{-2} GDD_0. \tag{1}$$

The pulse-front tilt γ also alters as a function of z (Fig. 2b). At the grating image plane ($\Delta z = 0$), γ_0 is independent of GDD_0 and obtained using:

$$|\gamma_0| = \tan^{-1}\left(\frac{m\lambda\rho}{M n_g \cos\theta_d}\right), \tag{2}$$

where n_g is the group index of the nonlinear crystal. For non-zero Δz, the GDD acting on the spatially chirped pump pulse leads to a reduction of the pulse front tilt with increasing distance from the angular disperser, or its image respectively. Adding GDD_0 to the pulse therefore distorts this dependence.

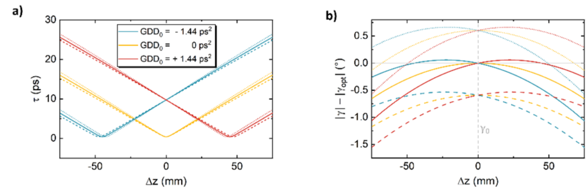

Figure 2: (a) Pulse duration vs Δz for initially compressed (yellow) and stretched (blue, red) pump pulses. Dashed ($\theta_d^{opt} + 1°$) and dotted lines (θ_d^{opt} - 1°) show the effect of θ_d.(b) The corresponding pulse-front tilt γ vs. Δz.

Experimental Results

Experimental scans of both GDD_0 and the longitudinal crystal position revealed a linear shift of the optimum crystal position with GDD_0 (see Fig. 3a) in excellent agreement with theory. Since at the temporal focus the same temporal properties of the pump pulse as for $GDD_0 = 0$, $\Delta z = 0$ are replicated, the pulse-front tilt γ matches γ_0 if the spatial pump properties do not vary significantly within Δz. This holds for tilted-pulse-front THz setups using a telescope for imaging and a large, collimated pump beam.

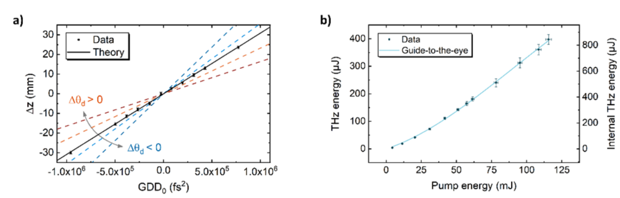

Figure 3: (a)The relative position of the crystal for maximum efficiency vs. GDD_0 on the pulse match the position computed for the temporal focus. (b) THz energy extracted from a setup pumped with stretched pump pulses ($GDD_0 = 1.44$ ps^2).

This result implies that one can find a longitudinal position z in the setup, at which the GDD_0 imposed on the pump pulse is annihilated while maintaining the pulse-front tilt γ_0. In other words, one can tune the laser system compressor such that transport of the pump beam to the setup is no longer an issue and - without the need for any additional compressor – recover the setup performance by shifting the crystal up/downstream by the appropriate distance Δz. To demonstrate this concept, our THz setup was moved ≈ 15 m further downstream in the pump beam and operated with pulses stretched to a duration of 10 ps (stretching factor of ≈ 25). To allow pumping with pulse energies > 100 mJ, the beam was spatially expanded with a telescope placed right before the THz setup.

Figure 3b shows the performance of this setup for $GDD_0 = 1.44$ ps^2 and $\Delta z \approx +44$ mm with $\theta_d = 56.49°$. Pulses with energies up to (400 ± 20) µJ were extracted for a moderate pump fluence (for cLN) of up to 160 mJ/cm^2. Despite a not yet fully optimized grating angle of the setup in this first proof-of-principle experiment, the measured energy ranks among the highest obtained from table-top tilted-pulse-front THz sources [10, 11].

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CONCLUSION

To conclude, we have studied both experimentally and numerically how the longitudinal crystal position in tilted-pulse-front setups is entangled with spatio-temporal pump pulse parameters such as pulse duration and pulse-front tilt. Maximum optical-to-terahertz conversion efficiency was found to coincide with the temporal focus of the pump laser. The position of this temporal focus can be controlled by the amount of pump pulse GDD_0. This is specifically relevant for fine-tuning the pulse parameters at a given interaction point and for scaling tilted-pulse-front setups towards higher pump energies, which both is demonstrated in this work for the first time. Single-cycle THz sources powered with such spatio-temporal manipulated pump pulses are promising to provide new levels of peak electric and magnetic fields to power novel THz based electron accelerators and manipulators. Moreover, the underlying techniques introduced in this work are foreseen to also profit other novel laser-based accelerator schemes such as dielectric and laser-plasma-based approaches.

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