Multi-cycle THz Pulse Generation and Start-to-end simulations on THz-driven Accelerators.

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Motivation

• Since the first demonstration of high-gradient particle acceleration [1], dielectric laser-driven acceleration (DLA) has gained relevance in recent years. Combining advances in manufacturing techniques with high-power lasers, **DLAs can reach acceleration gradients in the 1- 10 GV/m range**.

• However, **DLA faces several practical challenges**, namely the demand for very-low beam emittances, low bunch charges, and sub-femtosecond timing jitters [2].

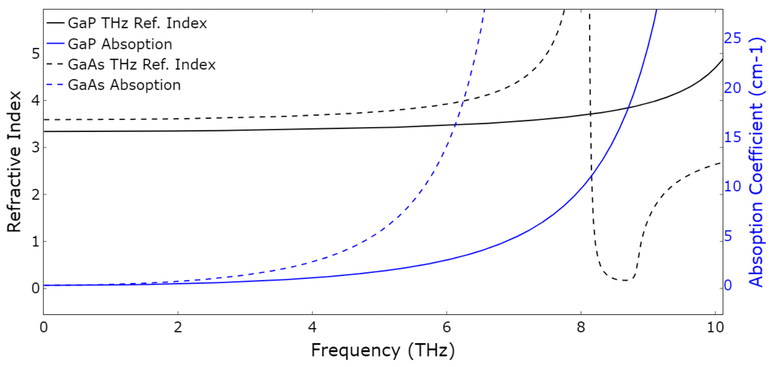
• Nevertheless, these limitations are softened when the accelerator is operated in the terahertz (THz) range (between 0.1 and 10 THz), often referred to as a dielectric THz-driven accelerator (DTA). THz wavelengths are one to two orders of magnitude longer than infrared, allowing higher bunch charges while reducing the manufacturing tolerance constraints. On the other hand, their higher frequency enables higher acceleration gradients than radio-frequency (RF). Several THz-driven linear accelerators have been proposed in the literature [3,4], showcasing their **potential for particle acceleration and beam manipulation**.

• In order to achieve high-gradient particle acceleration, high-field THz pulses are needed (from 0.1 to 10 GV/m). Optical rectification (OR) is a promising THz generation technique that could support high-field THz pulse generation in compact setups [5].

• In this work, we propose (i) an OR-based compact, multi-cycle THz source for high-THz-frequency generation (above 1 THz), and (ii) a multi-cycle pulse-driven DTA-integrated tapered parallel-plate waveguide (TPPWG) for particle acceleration [6]. Using this **novel structure**, proposed for the first time to the extent of the authors' knowledge, acceleration gradients higher than those of typical RF cavities can be achieved.

Multi-cycle high-frequency THz generation in orientation-patterned (OP) gallium arsenide and gallium phosphide

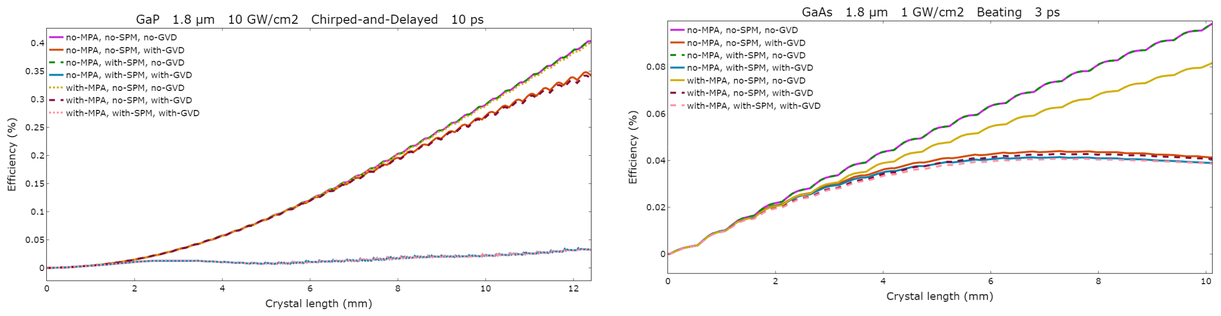
Gallium arsenide (GaAs) and gallium phosphide (GaP) are the best candidates for the generation of high-frequency (> 1 THz), multi-cycle THz pulses. Both nonlinear crystals are transparent in the infrared region, the difference between the THz refractive index and optical group index is low, **lower-orders multiphoton absorption can be avoided** [7] for pump wavelengths around 2 μm, and most importantly, they present low absorption in the THz range.



The THz refractive index (black) and absorption coefficient (blue) of GaP (solid line) and GaAs (dashed line).

Mechanisms Affecting THz Generation

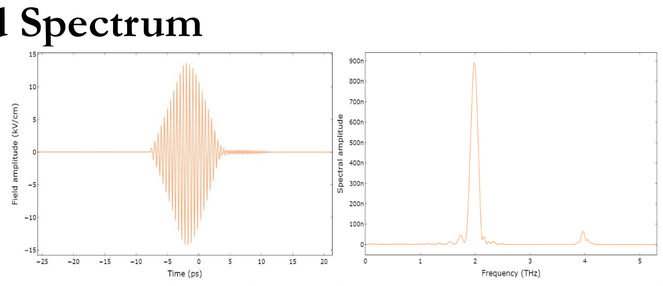
Several mechanisms occur during the propagation of the infrared pulse inside the crystal when generating THz radiation. THz absorption, difference-frequency generation (DFG) of the optical field, and free-carrier absorption (FCA) affect the generated THz pulse while (DFG) and sum-frequency generation (SFG) between the optical and THz fields, self-phase modulation (SPM), and multiphoton absorption (MPA) alter the optical pulse. Material group-velocity dispersion (GVD) also plays an important role, as shown in the figures below.



Optical-to-terahertz conversion efficiency for different models for (left) GaP and (right) GaAs when pumped at λ_{pump}=1.8 μm. In GaP, the pump consist of a 10-ps-long chirped-and-delayed pulse with a peak intensity of 10 GW/cm². For GaAs, the setup consist of the beating of two-narrowband, 3-ps-long Gaussian pulses, with peak intensity equal to 1 GW/cm². Note that in both setups, MPA is not the main limiting mechanism for the generation of THz radiation.

THz Pulse Waveform and Spectrum

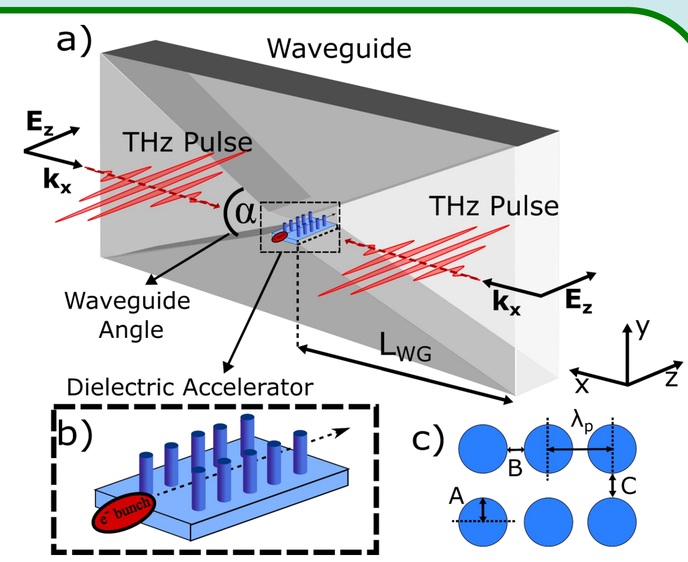
A 10-period-long OP-GaAs crystal (around 10.4 mm total length) is pumped by a burst of ten equidistant Gaussian pulses, each with a 220-fs pulse duration and a peak intensity of 0.32 GW/cm² for the generation of narrowband pulses centered at 2 THz.



THz pulse (left) waveform and (right) spectrum in OP-GaAs for the proposed setup

Tapered Parallel-plate Waveguide with an integrated Dielectric THz-driven Accelerator

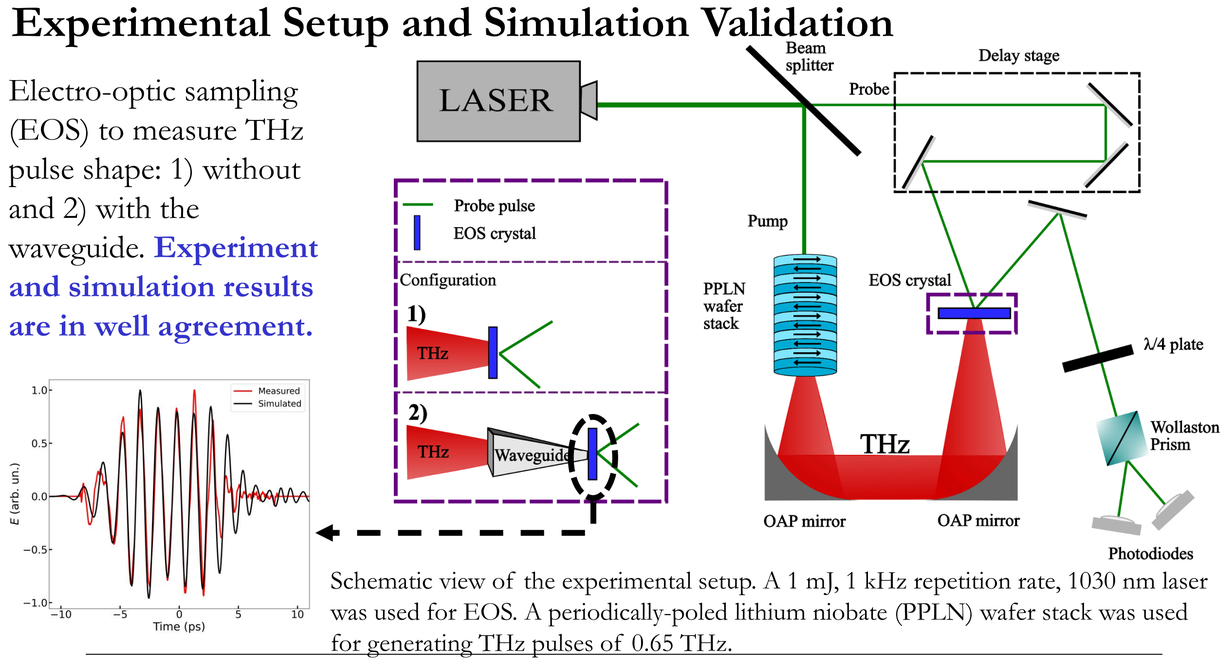
Two few-cycle linearly polarized THz pulses are focused laterally onto the waveguides. The pulses propagate through the waveguides until they reach the dielectric silicon pillars, which provide the means for net acceleration by near-fields [6]. Acceleration is achieved by timing the electron injection along the direction of the pillars' channel gap.



Schematic view of the accelerating structure. It operates at a central frequency of 0.65 THz ($\lambda_{THz} \approx 461$ μm) The parameters values are L_{WG} = 27 mm, α = 14°, A = 0.35 λ_{THz}, B = 0.3 λ_{THz} , C = 0.4 λ_{THz}, pillar height of 400 μm . The image is not to scale.

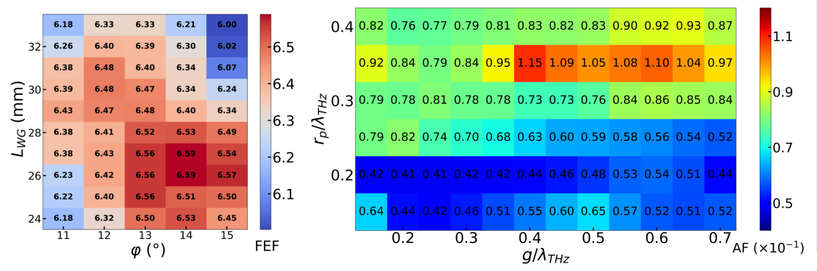
Experimental Setup and Simulation Validation

Electro-optic sampling (EOS) to measure THz pulse shape: 1) without and 2) with the waveguide. **Experiment and simulation results are in well agreement.**



Schematic view of the experimental setup. A 1 mJ, 1 kHz repetition rate, 1030 nm laser was used for EOS. A periodically-poled lithium niobate (PPLN) wafer stack was used for generating THz pulses of 0.65 THz.

Structure Optimization



Color mapped data of the electric field enhancement factor for WG length (left) and angle values and DTA's acceleration factor respect to the pillar radii and vacuum channel gap (right).

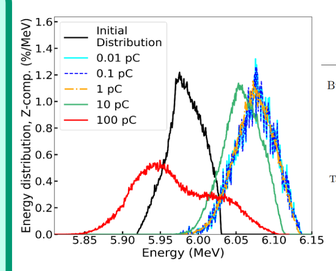
Parametric sweeps on the waveguide length and taper angle, pillars radius and the channel gap were performed to maximize the field enhancing factor (FEF) and the acceleration factor (AF), respectively. Both represents key figure-of-merits quantities for the accelerating structure.

$$AF = \frac{G_0}{E_{max}}, \qquad G_0 = \frac{q}{\lambda_p}\int_0^{\lambda_p} E_z(z(t),\phi)\,dz$$

Accelerator Performance

Particle-in-cell (PIC) simulations were used to calculate the projected kinetic energy distribution for several values of the bunch charge. As shown in the figure, the energy distribution does not change for values between 0.01 and 1 pC. For a bunch charge of 10 pC, the distribution shifts slightly towards lower energy, but keeping its shape.. An upper limit for the maximum bunch charge lies around 100 pC.
According to simulations, **an acceleration gradient of 120 MeV/m** can be achieved for an input THz field strength of around 100 MV/m [6].

$$E_z^{kin} = (\gamma_z - 1)mc^2,\ \gamma_z = 1/\sqrt{1-\beta_z^2},\ \beta_z = v_z/c$$



Bunch Parameter	Value
Transverse size	50 μm
Bunch length (FWHM)	250 fs
Energy	6 MeV
Energy spread	1 %
Angular spread	1 %
Emittance	0.4 μm rad
Bunch charge	from 0.01 pC to 100 pC

Table 1: Bunch parameters used in the PIC simulations.

The energy distribution for the initial bunch and the post-accelerated bunch for different bunch charges

Conclusion

- GaAs and GaP are well-suited for the generation of high-frequency-THz multi-cycle pulses (above 1 THz).
- Employing a pump wavelength of 1.8 μm to avoid lower-orders MPA is beneficial for generating higher-intensity THz pulses.
- A novel accelerating structure has been proposed, combining a TPPWG with an integrated DTA for the first time to the extent of the authors' knowledge.
- According to simulations, higher acceleration gradients than typical RF cavities can be achieved with current technology. These kinds of accelerators can improve the performance in ultrafast electron diffraction (UED) studies and high-resolution electron microscopy (HREM).
- The accelerating structure supports bunch charges up to 10 pC with minimal degradation of the bean quality [6].

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