TEMPORAL AND SPATIAL CHARACTERIZATION OF ULTRAFAST TERAHERTZ NEAR-FIELDS FOR PARTICLE ACCELERATION*

A. E. Gabriel†[1], M. A. K. Othman, M. C. Hoffmann, E. A. Nanni,
SLAC National Accelerator Laboratory, Menlo Park, USA
[1]also at University of California Santa Cruz, Santa Cruz, USA

Abstract

We have measured the THz near-field in order to inform the design of improved THz-frequency accelerating structures. THz-frequency accelerating structures could provide the accelerating gradients needed for next generation particle accelerators with compact, GV/m-scale devices. One of the most promising THz generation techniques for accelerator applications is optical rectification in LiNbO3 (LN) using the tilted pulse front method. However, accelerator applications are limited by significant losses during transport of THz radiation from the generating nonlinear crystal to the acceleration structure. In addition, the spectral properties of high-field THz sources make it difficult to couple THz radiation into accelerating structures. A better understanding of the THz near-field source properties is necessary for the optimization of THz transport and coupling. We have developed a technique for detailed measurement of the THz near-fields and used it to reconstruct the full temporal 3D THz near-field close to the LN emission face. Analysis of the results from this measurement will inform designs of novel structures for use in THz particle acceleration.

MOTIVIATION

THz frequency radiation is useful for many particle acceleration and beam manipulation applications [1-4]. Optical rectification in LiNbO3 using the tilted pulse front method is routinely used to generate THz pulses with energies in the tens of micro-joules and field strengths above 1 MV/cm [5]. Despite these strong fields, current THz acceleration methods are limited by significant losses during THz transport and coupling into the accelerating structure. Using the THz near-field for particle acceleration would significantly decrease losses due to beam transport. This approach requires the design of a novel structure that would generate THz radiation and use it for acceleration immediately. Designing an accelerating structure half out of LN would allow THz to be generated by optical rectification and used for electron acceleration without the need for THz transport. This approach would remove the THz losses incurred by beam transport, and allow for a longer THz interaction length. In addition, it would allow the structure to be constructed out of dielectrics, which would facilitate the implementation of advanced machining methods, such as femtosecond laser microfabrication, that can create complex geometries. These geometries can be optimized by simulation and optimization programs to maximize accelerating gradient. Preliminary simulations of half LN half silicon accelerator structures have been carried out using an electromagnetic simulation and automatic differentiation package Ceviche [6-8]. These simulations yielded a highly optimized structure geometry that is manufacturable using available machining methods, see Fig. 1. Updated shunt impedance calculations found a shunt impedance value of 1.3×10^{7} Ω/m.

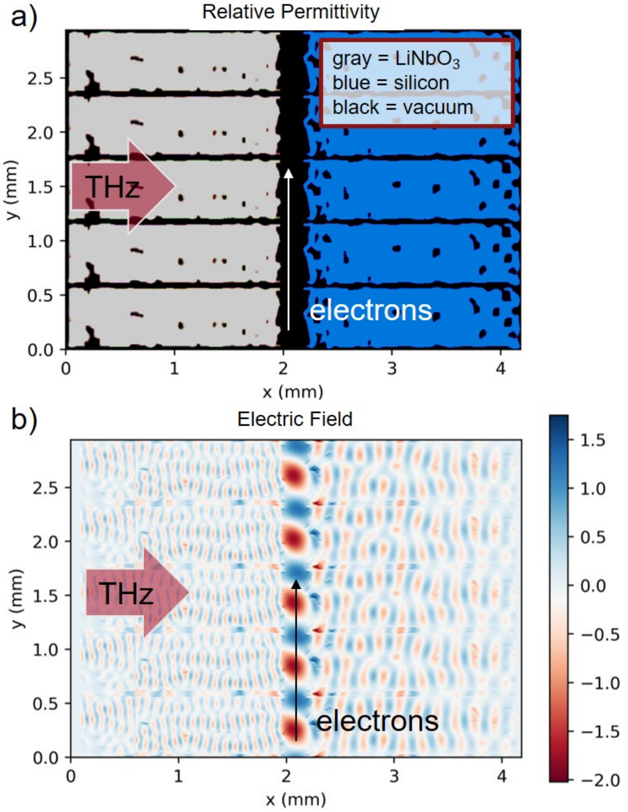

Figure 1: Final optimized geometry of a 5 period dielectric accelerator structure **(a)**. Electric fields produced by the structures in Figure 3 by a 0.5 THz continuous wave source incident from the left **(b)**. THz would be generated on the left side by optical rectification in LN. The other half of the structure would be constructed out of a material like silicon, which would act as a mirror.

A precise and robust understanding of the THz near field is needed in order to design this integrated THz generation and electron acceleration structure. We have conducted a measurement of the THz near-field from a tilted pulse front LN source in order to inform these designs, and help to develop better THz transport and coupling methods.

---

* Work supported by Department of Energy contract DE-AC02-76SF00515

† angabrie@slac.stanford.edu

METHODS

THz generation was carried out using optical rectification of 800 nm Ti:Sapphire laser pulses (2 mJ per pulse operating at 1 kHz) using the tilted pulse front method in a LN crystal, and measured using electro-optic sampling (EOS) in a 10 mm × 10 mm × 0.5 mm GaP crystal [9]. The GaP crystal was coated with highly reflective coating on one side and anti-reflective coating on the other, both at wavelength 800 nm. The GaP crystal was placed parallel to the exit plane of the LN with the highly reflective coating facing towards the LN and positioned within the near-field of THz radiation, as shown in Fig. 1. Standard EOS detection was used to detect the THz near-field [10]. The probe beam was timed to arrive over a range of times when the THz pulse was exiting the LN, allowing the full temporal evolution of the THz pulse to be captured. A 10 cm focal length plano-convex lens mounted on a 2D translation stage was used to raster the probe beam across the face of the GaP crystal in a grid pattern collecting 2D images at each arrival time. To investigate the observed relationship between the temporal delay in the emission of the THz pulse and the diffraction grating angle in the tilted pulse front setup we carried out a series of measurements at different diffraction grating angles. The setup was re-optimized and then measurements were carried out varying the diffraction grating angle by ±1° from the ideal angle θ obtained through experimental optimization of pulse energy. A series of 1D images were taken at each angle keeping all other parameters the same.

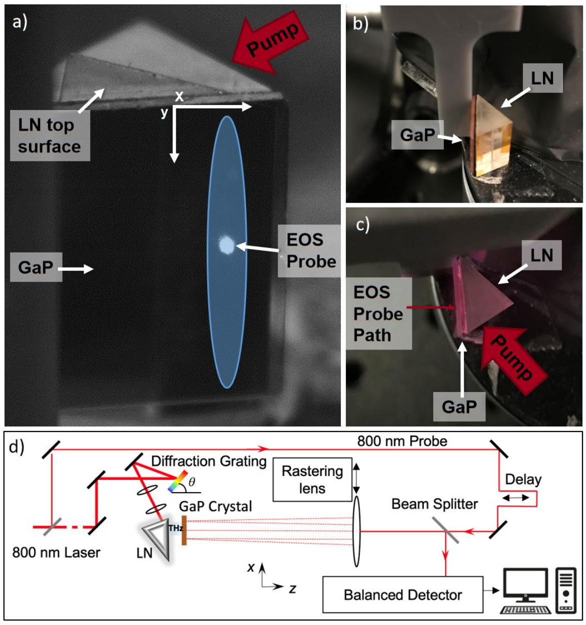

Figure 2: Images of **(a)** front, **(b)** side, and **(c)** top view of EOS setup showing GaP crystal, LN crystal, THz generation pump beam, EOS probe beam, and coordinate system used in Fig. 2. Light blue oval in **(a)** indicates approximate region of THz emission. **(d)** Full experimental setup showing THz generation with tilted pulse fronts, lens used for spatial rastering of the EOS probe beam, and delay stage used to vary the time of arrival of the EOS probe beam.

RESULTS

Our results show a temporal delay in the emission of the pulse as a function of lateral delay on the LN surface. This delay can be seen as movement of the THz pulse peak in the x direction of the plots in Fig. 3 [11]. Results from measurements varying the diffraction grating were analyzed to determine the effect on the maximum pulse amplitude and central frequency (Fig 4). The results were also analyzed to determine the change in speed of the lateral motion of the pulse (Table 1). These results show that the lateral delay of the pulse can be tuned by varying the diffraction grating angle, and that it is possible to control the amplitude and frequency of the near-field. Tuning of the observed temporal delay of THz emission could allow synchronous electron acceleration. Manipulation of the amplitude and central frequency could be optimized for different electron acceleration and beam manipulation applications.

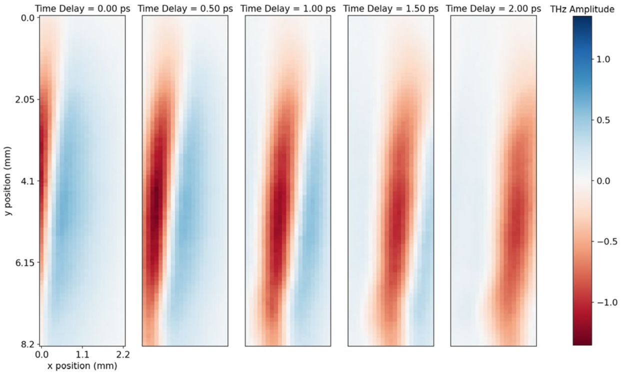

Figure 3: 2D images of the THz near-field taken 0.2 mm from the exit of the LN. Images were taken with 8 mm × 2 mm spatial grid size, 0.1 mm spatial resolution, 2 ps time range, and 0.1 ps time resolution. 5 representative images are shown at different time of arrival values.

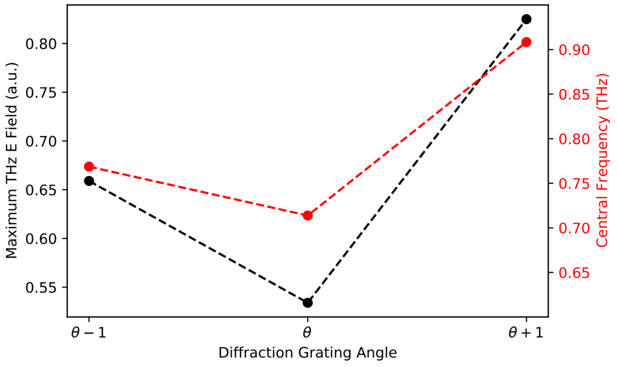

Figure 4: Diffraction grating angle was varied over a series of 2 mm lateral (x direction on Fig. 2) line measurements with 0.1 mm resolution located at approximately y = 4.5 mm in the plots in Fig. 3. The GaP crystal was place 0.3 mm from the exit of the LN. Data was taken over a 6 ps time range with 0.1 ps resolution. Plots above show the maximum THz amplitude and central frequency collected.

Table 1: Change in Temporal Delay of THz Pulse

Diffraction Grating Angle	**Lateral Speed [mm/ps]**
θ-1	0.73± 0.06
θ	0.85±0.04
θ+1	0.99± 0.05

CONCLUSION

We have conducted measurements of the THz near-field generated via optical rectification in $LiNbO_3$ with excellent spatial and temporal resolution. We show a temporal delay in the emission of the pulse as a function of lateral position on the LN surface. The relation between the temporal delay and diffraction grating angle was characterized, showing that the temporal delay could be tuned by varying the diffraction grating angle. These results show that The THz near-field from a tilted pulse front LN source is highly applicable to integrated THz generation and electron acceleration. The temporal delay of the THz pulse could be tuned for synchronous electron acceleration, yielding significant gains in electron acceleration. In addition, the THz pulse amplitude and central frequency can be changed for different beam manipulation applications. These results motivate the design of an integrated THz generation and electron acceleration structure which could take advantage of the THz near-field. These measurements will inform updated simulations, and aid in improving methods of beam transport and coupling.

REFERENCES

[1] H. Xu *et al.*, "Cascaded high-gradient terahertz-driven acceleration of relativistic electron beams", *Nat. Photonics*, vol. 15, pp. 426-430, 2021. `doi:10.1038/s41566-021-00779-x`

[2] M. T. Hibberd *et al.*, "Acceleration of relativistic beams using laser-generated terahertz pulses", *Nat. Photonics*, vol. 14, pp. 755–759, 2020.

[3] E. C. Snively *et al.*, "Femtosecond compression dynamics and timing jitter suppression in a terahertz-driven electron bunch compressor", in *Phys. Rev. Lett.* vol. 124, p. 054801, 2020.

[4] M. A. K. Othman *et al.*, "Terahertz Driven Compression and Time-Stamping Technique for Single-shot Ultrafast Electron Diffraction", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, SP, Brazil, May. 2021, pp. 492-493. `doi:10.18429/JACoW-IPAC2021-MOPAB141`

[5] S. S. Dhillon *et al.*, "The 2017 terahertz science and technology roadmap", *J. Phys. D: Appl. Phys.*, vol. 50, p. 043001, 2017.

[6] T. W. Hughes *et al.*, "Forward-Mode Differentiation of Maxwell's Equations", *ACS Photonics*, vol. 6, pp. 3010-3016, 2019.

[7] `https://github.com/fancompute/ceviche`

[8] A. E Gabriel and E. A. Nanni, "Investigation of Optimization of Dielectric Terahtertz Acceleration Structures", in *Proc.* 12th *Int. Particle Accelerator Conf. (IPAC'*21), Campinas, SP, Brazil, May. 2021, pp. 502-504. `doi:10.18429/JACoW-IPAC2021-MOPAB144`

[9] A. J. L. Adam, "Review of Near-Field Terahertz Measurement Methods and Their Applications", *J Infrared Milli Terahz Waves*, vol. 32, p. 976, 2011.

[10] P. E. Powers, "Electro-optic Sampling for Terahertz Detection", *Field Guide to Nonlinear Optics (Society of Photo-Optical Instrumentation Engineers*, 2013.

[11] A. E. Gabriel, M. A. K. Othman, M. C. Hoffmann, and E. A. Nanni, "Temporal and Spatial Characterization of Ultrafast THz Near-Fields", in *Proc. Conf. on Laser Electro-Optics (CLEO'22)*, San Jose, CA, USA, May 2022.