PROGRESS IN DEVELOPING AN ACCELERATOR ON A CHIP*

R. J. England†, SLAC National Accelerator Laboratory, Menlo Park, CA USA
P. Hommelhoff, Friedrich Alexander University, Erlangen, Germany
R. L. Byer, Stanford University, Stanford, CA USA

Abstract

Acceleration of particles in photonic nanostructures fabricated using semiconductor manufacturing techniques and driven by ultrafast solid state lasers is a new and promising approach to developing future generations of compact particle accelerators. Substantial progress has been made in this area in recent years, fueled by a growing international collaboration of universities, national laboratories, and companies. Performance of these micro-accelerator devices is ultimately limited by laser-induced material breakdown limits, which can be substantially higher for optically driven dielectrics than for radio-frequency metallic cavities traditionally used in modern particle accelerators, allowing for 1 to 2 order of magnitude increase in achievable accelerating fields. The lasers required for this approach are commercially available with moderate (micro-Joule class) pulse energies and repetition rates in the MHz regime. We summarize progress to date and outline potential near-term applications and offshoot technologies.

INTRODUCTION

Constraints on the size and cost of accelerators have inspired a variety of advanced acceleration concepts for making smaller and more affordable particle accelerators. The use of lasers as an acceleration mechanism is particularly attractive due to the intense electric fields they can generate combined with the fact that the solid state laser market has been driven by extensive industrial and university use toward higher power and lower cost over the last 20 years. Dielectrics and semiconductor materials have optical damage limits corresponding to acceleration fields in the 1 to 10 GV/m range, which is orders of magnitude larger than in conventional accelerators. Such materials are also amenable to rapid and inexpensive CMOS and MEMS fabrication methods developed by the integrated circuit industry. These technological developments over the last two decades, combined with new concepts for efficient field confinement using optical waveguides and photonic crystals, have inspired an international community of university, government laboratory, and industrial researchers to develop on-chip integrated particle accelerators driven by micro-Joule to milliJoule class infrared lasers, which we refer to as *dielectric laser accelerators* (DLA).

As an advanced accelerator concept, the DLA approach offers some unique advantages. The acceleration mechanism is inherently linear and occurs in a vacuum region in a static structure. In addition to the stability benefits this affords, the acceleration effect is inherently dependent on the phase of the laser field, which makes it possible to dynamically fine-tune accelerator performance by manipulation of the incident laser phase profile. Gradients on the GV/m scale have already been demonstrated with energy gains exceeding 0.3 MeV for a few-fC beam, and wall plug efficiencies comparable or superior to conventional approaches appear feasible. The primary supporting technologies (solid state lasers and nanofabrication) are mature and already at or near the capabilities required to develop an integrated on-chip accelerator based on this approach. Development of near-term applications in medicine, science, and industry could utilize the unique capabilities of these sources while providing platforms for further technological development.

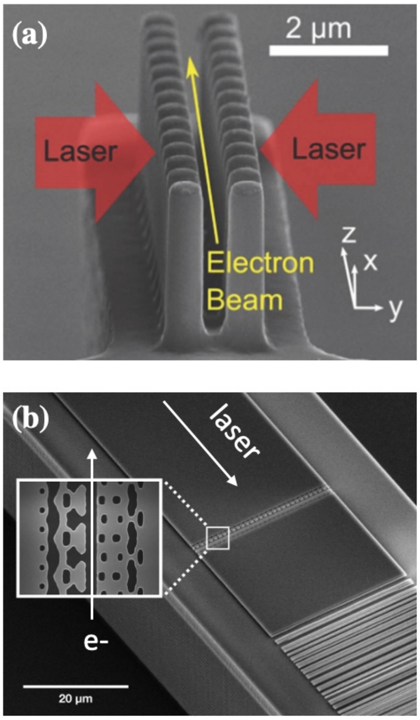

Figure 1: Recently demonstrated DLA structures based on (a) the dual-pillar design [1] and (b) an optical waveguide-coupled approach utilizing computer-aided *inverse design* to produce highly optimized structures [2].

STATE OF THE ART IN ON-CHIP PARTICLE ACCELERATORS

The field of particle acceleration using laser-driven dielectric structures has undergone significant experimental progress within the last decade. In 2013, the first demonstra-

---

[*] Work supported by the Gordon and Betty Moore Foundation

[†] england@slac.stanford.edu

tions of acceleration in a DLA were performed by teams at SLAC and at Friedrich Alexander University [3, 4]. Since these initial proof of principle experiments, different structures, materials, and lasers have been used to improve performance. At Stanford, silicon dual pillar structures, illuminated by an Ytterbium fiber laser beam, as shown in Fig. 1(a), were used to accelerate 100 keV electrons with an acceleration gradient of 370 MeV/m [5]. To increase the accelerating gradient further, short pulsed lasers have recently been used. By using a 20 fs pulse length laser, the group at FAU Erlangen was able to accelerate 28 keV electrons with a gradient of 210 MeV/m [6]. In subsequent experiments in collaboration between UCLA and SLAC, a 45 fs pulse length Ti:Sapphire laser was used to demonstrate average accelerating gradients of up to 850 MeV/m on a 8 MeV electron beam in an enclosed fused silica DLA, with peak accelerating fields of 1.8 GV/m [7]. By adding a pulse front tilt of the laser pulses to extend the interaction distance, greater than 0.3 MeV of energy gain has been demonstrated [8]. Additionally, other features of the accelerating fields (e.g. their optical microbunch structure and their deflecting forces) have been probed. The transverse control of 28 keV electrons has been demonstrated with both transverse deflecting structures (a rotated silicon grating) and focusing structures (a Si grating with parabolically shaped grating teeth) [6]. At the infrared laser frequencies employed, the accelerated electrons have an intrinsic sub-cycle pulse structure, or *micro-bunching*, on the sub-fs scale, which has been demonstrated in experiments with measured pulse durations as low as 270 attoseconds [9, 10]. This intrinsic optical modulation of the electron beam is a unique feature of the DLA approach, with potential applications in ultrafast electron diffraction (UED) and quantum information science (QIS).

Although 2-stage acceleration within a single DLA device has been demonstrated [11], most DLA experiments to date have included only a single acceleration stage. In order to advance to a fully integrated multi-stage accelerator, as illustrated conceptually in Fig. 2, compatible electron sources, guided wave systems, and optical focusing and confinement of the electrons are required. Considerable effort at the university level has been directed towards development of compact electron sources based on laser-assisted field emission from nanotips, which can produce electron beams with sub-nanometer normalized emittances [12]. Such miniaturized low-current particle sources are well adapted to the DLA approach and have been incorporated into compact benchtop DLA test platforms [13]. Although tip-based sources have demonstrated exceptional brightness, they typically produce very low-current beams. A potential solution is to incorporate multiple beam channels in a matrixed photonic crystal configuration coupled to an array of nano-emitters, as described in Ref. [14]. In addition, requirements for compatible optical waveguide implementations have been systematically studied [15], and the first integrated waveguide-coupled on-chip accelerator experimentally demonstrated, as shown in Fig. 1(b)[2]. The latter demonstration additionally employs computer-aided adjoint variable methods (or *inverse design*), which has proven to be a powerful technique for producing non-intuitive but highly optimized photonic designs possessing an almost organic appearance, as seen in the inset of Fig. 1(b).

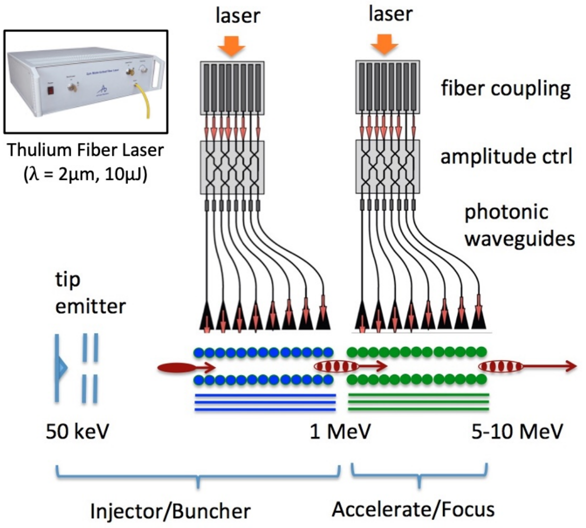

Figure 2: Conceptual illustration of an integrated on-chip accelerator system including electron emitter and optical phase and amplitude control over multiple acceleration stages, which could be powered by commercially available rack-mounted fiber lasers (inset).

PARTICLE FOCUSING AND CONFINEMENT

For long-distance particle transport there is a serious need for a beam collimation system. Techniques for DLA have been proposed that utilize the laser field itself to produce a ponderomotive focusing force either by excitation of additional harmonic modes (*spatial harmonic focusing*) or by introducing drifts that alternate the laser field between accelerating and focusing phases to simultaneously provide acceleration as well as longitudinal and transverse confinement (*alternating phase focusing* or APF) [16, 17]. In simulation, such focusing techniques can adequately confine a particle beam to a narrow channel and overcome the resonant defocusing of the accelerating field. New structure designs and experiments are currently underway to test these approaches. So far, active beam transport with the help of APF has been shown to work at optical frequencies: the electron throughput through a 225 nm narrow and nearly 80 μm long nanostructure was increased by close to factor of 3 based on APF forces [18], see Fig. 3. However, for acceleration to large energies, a generalization to 3D of the originally proposed two-dimensional schemes is required. As discussed in [19], the 3D scheme has advantages at low energy, where the confinement to the extremely small aperture can also be provided in the vertical axis. Recently, based on this scheme and using Silicon-on-Insulator (SOI) wafers, a completely

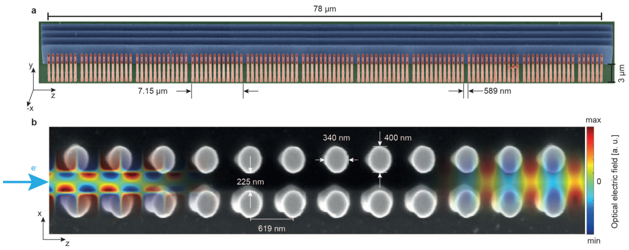

Figure 3: Alternating phase focusing (APF) structure. Macrocells are separated by gaps, which lead to a phase jump between the propagating electrons and the driving mode, facilitating APF operation at optical frequencies. Bottom panel shows longitudinal (right) and transverse (left) forces acting on the electrons by virtue of the laser-generated co-propagating optical mode. Both forces act at the same time. See [18] for details.

scalable multi-stage accelerator could be designed [20]. At high energy, the 3D APF scheme allows stronger focusing gradients, since the square-sum of the two focusing constants scales with γ^{-2} [19], such that in a counter-phase arrangement the two transverse planes can exhibit focusing gradients that are not constrained by the beam energy. This allows for structure designs employing a single high-damage-threshold material, allowing for shorter focusing periods and higher emittances than the earlier 2D structures [21].

APPLICATIONS FOR ON CHIP ACCELERATORS

With tabletop sources now coming into operation in university labs, near-term applications that utilize presently available low-current beams with moderate particle energies in the 100 keV to few MeV range are being actively pursued (see Fig. 4 and [22]).

Due to the intrinsic optical-scale bunch structure, with sub-femtosecond bunch duration, compact electron sources for ultrafast science and electron diffraction studies are among the most promising applications. Compact accelerators with target energies in the few MeV range for medical dosimetry also provide a compelling near-term use for DLA technology. An ultracompact self-contained multi-MeV electron source based on integrated photonic particle accelerators could enable minimally invasive cancer treatments and adjustable dose deposition in real-time, with improved dose control. For example, one could envision an encapsulated micro-accelerator built onto the end of a fiber-optic catheter placed within a tumor site using standard endoscopic methods, allowing a doctor to deliver the same or higher radiation dose to what is provided by existing external beam technologies, with less damage to surrounding tissue [23, 24]. The manufacturing and operating costs based on low-cost or disposable chips, powered by an external fiber laser, could be much lower than those for conventional radiation therapy machines, and the robustness of such systems compared to conventional accelerators could be even more favorable.

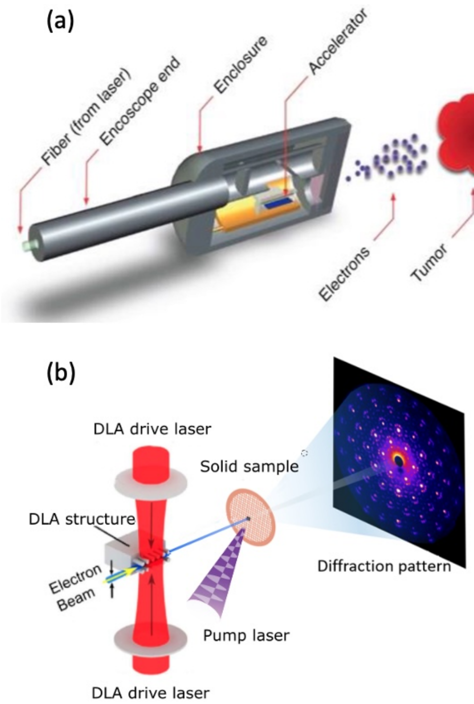

Figure 4: Promising near-term applications for laser-driven accelerators include (a) endoscopic medical radiation therapy delivery devices, (b) tabletop sources for MeV ultrafast electron diffraction studies.

Pulse trains of attosecond electron bunches are intrinsic to the DLA approach and could provide excellent probes of transient molecular electronic structure. Recently, this fine time-scale structure has been experimentally measured (with bunch durations from 270 to 700 attoseconds) and injected into a subsequent acceleration stage to perform fully on-chip bunching and net acceleration demonstrations [9, 10]. The far greater flexibility of on-chip attosecond electron sources could be important complements to optical attosecond probes based on high harmonics or attosecond X-ray free electron lasers (FELs). The capabilities of chip-scale electron probes could be transformational for studies of chemical impurities and dopants in materials and could enable a unique class of compact tabletop electron sources for ultrafast electron microscopy (UEM). Since both the accelerator and associated drive laser and peripherals are all compact enough to fit on a tabletop, this would enable the construction of compact and flexible attosecond electron and photon sources that can resolve atomic vibrational states in crystalline solids in both spatial and temporal domains simultaneously. This could lead to improved understanding of the dynamics of chemical reactions at the level of individual molecules, the dynamics of condensed matter systems, and photonic control of collective behaviors and emergent phenomena in quantum systems.

The difference in bunch charge and duration for optically accelerated electron beams also points to the potential for future light sources for generation of attosecond-scale pulses of extreme ultraviolet (EUV) or X-ray radiation, with the potential to produce extremely bright electron beams that are suitable for driving superradiant EUV light in a similarly optical-scale laser-induced undulator field [25]. Furthermore, because of the few-femtosecond optical cycle of near infrared mode-locked lasers, laser-driven free electron lasers (FELs) could potentially generate attosecond X-ray pulses to probe matter on even shorter time scales than is possible today. Laser-driven dielectric undulators have been proposed and could be fabricated using similar photolithographic methods used to make on-chip accelerators [26, 27]. Combining the high gradient and high brightness of advanced accelerators with novel undulator designs could enable laboratory-scale demonstrations of key concepts needed for future EUV and X-ray lasers that hold the potential to transform the landscape of ultrasmall and ultrafast sciences. The optical-scale FEL regime has not been extensively studied before and questions arise as to how well the beam will behave in such structures and how well it will ultimately perform. The theoretical and numerical tools to model these processes need to be developed in order to guide experimental studies of attosecond electron and photon generation. Various technical challenges to developing near-term applications for tabletop laser accelerators (including high-energy gain, multi-stage beam transport, and higher average beam power) must also be addressed in order to reach the stringent beam quality and machine requirements for longer-term and higher energy applications in basic energy science and high energy physics. The near-term applications outlined above therefore represent an intermediate advancement of the technology towards ultimately desired performance levels. Further development of these applications also holds the potential to leverage both scientific and industrial interests that could facilitate more rapid development and support.

CONCLUSION

Particle acceleration in microstructures driven by ultrafast solid state lasers is a rapidly evolving area of advanced accelerator research, leading to a variety of concepts based on planar-symmetric dielectric gratings, free-standing silicon pillars, and optimized inverse designed structures. This approach, which we refer to as a *dielectric laser accelerator* (DLA), leverages well-established industrial fabrication capabilities and the commercial availability of tabletop lasers to reduce cost, with demonstrated axial accelerating fields in the GV/m range. Wide-ranging international efforts have significantly improved understanding of gradient limits, structure design, particle focusing and transport, staging, and development of compatible low-emittance electron sources. With a near-term focus on low-current MeV-scale applications for compact scientific and medical instruments, as well as novel diagnostics capabilities, on-chip laser-driven accelerators have key benefits that warrant further development, including modest power requirements, stability, and readiness of supporting technologies.

ACKNOWLEDGEMENTS

This work was supported in part by the Gordon and Betty Moore Foundation (GBMF4744), the U.S. Department of Energy (DE-AC02-76SF00515) and the European Research Council (Adv. Grant AccelOnChip, 884217).

REFERENCES

[1] K. J. Leedle *et al.*, "Phase-dependent laser acceleration of electrons with symmetrically driven silicon dual pillar gratings," *Opt. Lett.*, vol. 43, no. 9, pp. 2181–2184, 2018.

[2] N. Sapra *et al.*, "On-Chip Integrated Laser-Driven Particle Accelerator," *Science*, vol. 367, pp. 79–83, 6473 2020.

[3] E. A. Peralta *et al.*, "Demonstration of electron acceleration in a laser-driven dielectric microstructure," *Nature*, vol. 503, pp. 91–94, 2013.

[4] J. Breuer and P. Hommelhoff, "Laser-based acceleration of non-relativistic electrons at a dielectric structure," *Phys. Rev. Lett.*, vol. 111, p. 134 803, 2013.

[5] K. J. Leedle, R. F. Pease, R. L. Byer, and J. S. Harris, "Laser Acceleration and Deflection of 96.3 keV Electrons with a Silicon Dielectric Structure," *Optica*, vol. 2, pp. 158–161, 2015.

[6] M. Kozák *et al.*, "Dielectric laser acceleration of sub-relativistic electrons by few-cycle laser pulses," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 865, no. Supplement C, pp. 84–86, 2017, `doi:10.1016/j.nima.2016.12.051`

[7] D. Cesar *et al.*, "High-field nonlinear optical response and phase control in a dielectric laser accelerator," *Nature Comm. Phys.*, vol. 1, no. 4, pp. 1–7, 2018.

[8] D. Cesar *et al.*, "Enhanced energy gain in a dielectric laser accelerator using a tilted pulse front laser," *Optics Express*, 2018, `doi:10.48550/arXiv.1804.00634`

[9] D. S. Black *et al.*, "Net Acceleration and Direct Measurement of Attosecond Electron Pulses in a Silicon Dielectric Laser Accelerator," *Phys. Rev. Lett.*, vol. 123, p. 264 802, 2019.

[10] N. Schoenenberger, A. Mittelbach, P. Yousefi, J. McNeur, U. Niedermayer, and P. Hommelhoff, "Generation and Characterization of Attosecond Microbunched Electron Pulse Trains via Dielectric Laser Acceleration," *Phys. Rev. Lett.*, vol. 123, p. 264 803, 2019.

[11] J. McNeur *et al.*, "Elements of a dielectric laser accelerator," *Optica*, vol. 5, no. 6, pp. 687–690, 2018.

[12] A. C. Ceballos, "Silicon photocathodes for dielectric laser accelerators," Ph.D. dissertation, Stanford University, 2019.

[13] T. Hirano *et al.*, "A compact electron source for the dielectric laser accelerator," *Applied Phys. Lett.*, vol. 116, p. 161 106, 2020.

[14] Z. Zhao *et al.*, "Design of a multichannel photonic crystal dielectric laser accelerator," *Photonics Research*, vol. 8, pp. 1586–1598, 10 2020.

[15] T. W. Hughes *et al.*, "On-Chip Laser-Power Delivery System for Dielectric Laser Accelerators," *Phys. Rev. Applied*, vol. 9, p. 054 017, 2018.

[16] B. Naranjo, A. Valloni, S. Putterman, and J. B. Rosenzweig, *Phys. Rev. Lett.*, vol. 109, p. 164 803, 2012.

[17] U. Niedermayer, T. Egenolf, O. Boine-Frankenheim, and P. Hommelhoff, "Alternating phase focusing for dielectric laser acceleration," *Phys. Rev. Lett.*, vol. 121, p. 214 801, 2018.

[18] R. Shiloh *et al.*, "Electron phase-space control in photonic chip-based particle acceleration," *Nature*, vol. 597, pp. 498–502, 2021.

[19] U. Niedermayer, T. Egenolf, and O. Boine-Frankenheim, "Three dimensional alternating-phase focusing for dielectric-laser electron accelerators," *Phys. Rev. Lett.*, vol. 125, p. 164 801, 2020.

[20] U. Niedermayer, J. Lautenchläger, T. Egenolf, and O. Boine-Frankenheim, "Design of a scalable integrated nanophotonic electron accelerator on a chip," *Phys. Rev. Applied*, vol. 16, p. 024 022, 2021.

[21] U. Niedermayer, K. Leedle, P. Musumeci, and S. A. Schmid, "Beam dynamics in dielectric laser acceleration," *J. Instrum. this issue*, 2022.

[22] R. J. England *et al.*, "Considerations for a TeV collider based on dielectric laser accelerators," *Journal of Instrumentation*, vol. 17, P05012, 2022.

[23] R. J. England *et al.*, "Conceptual layout for a wafer-scale dielectric laser accelerator," in *Proc. of the 2014 Advanced Accelerator Concepts Workshop, San Jose, CA*, 2014.

[24] M. Fazio *et al.*, "Basic Research Needs Workshop on Compact Accelerators for Security and Medicine," *Report of the Department of Energy Office of Science Workshop, May 6-8, 2019*, 2020, `https://science.osti.gov/-/media/hep/pdf/Reports/2020/CASM_WorkshopReport.pdf`

[25] R. J. England and Z. Huang, "Dielectric and other non-plasma accelerator based compact light sources," in *Proc. of the Future Light Source Workshop (FLS 2018), Shanghai, China*, 2018, WEA1PL02.

[26] T. Plettner and R. L. Byer, "Proposed dielectric-based microstructure laser-driven undulator," *Phys. Rev. ST Accel. Beams*, vol. 11, p. 030 704, 2008.

[27] T. Plettner, R. L. Byer, C. McGuinness, and P. Hommelhoff, "Photonic-based laser driven electron beam deflection and focusing structures," *Phys. Rev. ST Accel. Beams*, vol. 12, p. 101 302, 2009.