SLAC-PUB-15782

MANUFACTURE AND TESTING OF OPTICAL-SCALE ACCELERATOR STRUCTURES FROM SILICON AND SILICA*

R. J. England, E. R. Colby, R. Laouar, C. M. McGuinness, B. Montazeri, R. J. Noble,
E. A. Peralta, K. Soong, J. Spencer, D. Walz, Z. Wu, SLAC, Menlo Park, CA 94025, USA
M. Qi, C. Lee, Y. Xuan, L. Fan, L. T. Varghese, Purdue Univ., West Lafayette, IN 47907, USA
R. L. Byer, C-M. Chang, K. J. Leedle, Stanford Univ., Stanford CA, USA
B. Cowan, Tech-X, Boulder CO, USA

Abstract

We report on recent progress in the design, manufacture and testing of optical-scale accelerator structures made from silicon and silica. The potential of these structures for the development of extremely compact, efficient, and low cost accelerators producing attosecond electron pulses will be discussed, together with various possible applications.

INTRODUCTION

Dielectric laser acceleration (DLA) refers to the use of infrared (IR) lasers to accelerate charged particles inside of a vacuum channel in a dielectric structure. The channel acts as both a vacuum region where an electron beam can propagate and as a waveguide to confine an electromagnetic accelerating mode. Assuming that the guiding channel's transverse dimensions are of the order of the drive laser wavelength (i.e. 1 to 10 microns) the power coupling efficiency to the particle bunches can in principle be in the tens of percent, with optimal efficiency at bunch charges of 1 to 20 fC [1]. In order for successive bunches to sit in the accelerating phase of the wave, the requisite bunch durations are on the attosecond scale with intrabunch spacing equal to the laser wavelength (or an integer multiple thereof). A technique for generating the requisite optically microbunched attosecond scale beams was recently demonstrated at SLAC [2], and recent work in field emission needle-tip emitters demonstrates that electron beams with the requisite charge and emittance requirements are within reach [3]. As a result of the various technical requirements just mentioned, the beam parameters for an accelerator based on this technology would be quite different from both traditional machines and other advanced schemes.

DLA offers several compelling potential advantages over traditional microwave cavity accelerators. Accelerating gradient is limited by the breakdown threshold for damage of the confining structure in the presence of intense electromagnetic fields. In the DLA scheme operating at typical laser pulse lengths of 0.1 to 1 ps, the laser damage fluences for dielectric materials such as silicon and glass correspond to peak surface electric fields of 400 to 2000 MV/m. This is to be compared with breakdown limits of 40 to 100 MV/m for metal cavities. The corresponding gradient enhancement represents a reduction in active length of the accelerator between 1 and 2 orders of magnitude. Power sources for DLA-based accelerators (lasers) are cheaper than microwave sources (klystrons) for equivalent average power levels due to the wider availability and private sector investment in commercial laser sources. Due to the high laser-to-particle coupling efficiency, required pulse energies are consistent with tabletop microjoule class lasers. Fabrication techniques for constructing three-dimensional dielectric structures with nanometer-level precision are well established in the semiconductor industry and the capillary fiber industry. Once a suitable fabrication recipe is developed, on-chip DLA devices with multiple stages of acceleration and waveguides for coupling power to and from the structure could be manufactured at low per-unit cost on silicon wafers.

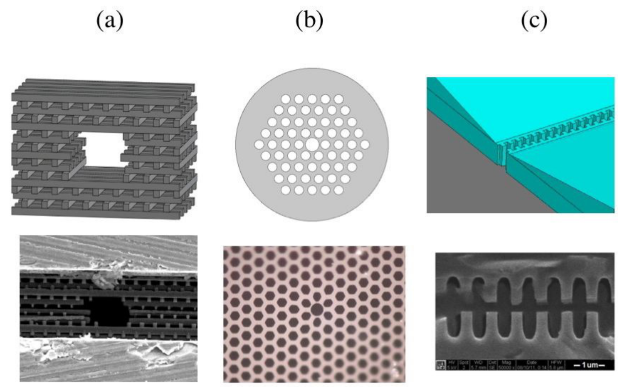

Figure 1: Three dielectric laser accelerator topologies: (a) a 3D silicon photonic crystal structure, (b) a hollow-core photonic bandgap fiber, and (c) a dual-grating structure, showing conceptual illustration (top) and recently fabricated structures (bottom).

To reach 10 TeV center-of-mass energies, a next generation lepton collider based on traditional RF microwave technology would need to be over 100 km in length and would likely cost tens of billions of dollars to build. Due to the inverse scaling of the interaction cross section with energy, the required luminosity for such a machine would be as much as 100 times higher than proposed 1-3TeV machines (ILC and CLIC), producing a luminosity goal of order 10^{36} $cm^{-2}s^{-1}$. In attempting to meet these requirements in a smaller cost/size footprint using advanced

* Work supported by U.S. Department of Energy under Grants DE-AC02-76SF00515, DE-FG06-97ER41276 and by DARPA Grant N66001-11-1-4199.

Presented at the 3rd International Particle Accelerator Conference (IPAC 2012)
New Orleans, Louisiana, USA, May 20 - 25, 2012

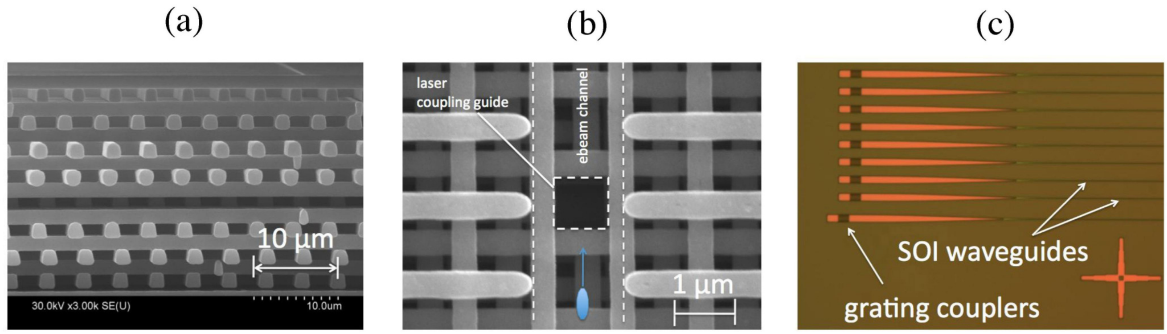

Figure 2: Recently fabricated accelerator components: (a) 17-layer silicon woodpile with 4 μm period constructed by an alternate membrane stacking technique; (b) cross section of photolithography-produced silicon woodpile with accelerating channel (vertical) and transverse laser coupling guide (into page); (c) grating-to-SOI couplers for coupling of optical fiber laser into on-chip power delivery wavegiudes.

acceleration schemes, the increased beam energy spread from radiative loss during beam-beam interaction (beamstrahlung) at the interaction point becomes a pressing concern. Since the beamstrahlung parameter is proportional to bunch charge, a straightforward approach to reducing it is to use small bunch charges, with the resulting quadratic decrease in luminosity compensated by higher repetition rates. This is the natural operating regime of the DLA scheme, with the requisite average laser power and high ($>$10 MHz) repetition rates to be provided by modern fiber lasers.

CURRENT STATE OF THE ART IN OPTICAL-SCALE ACCELERATOR DESIGN

A future DLA-based linear collider will require the development of high-gradient accelerator structures as well as suitable diagnostics and beam manipulation techniques, including compatible small-footprint deflectors, focusing elements, and beam position monitors. Integration of these subcomponents into a single optical-scale accelerator that can be mass-produced using available nanofabrication techniques requires that they be constructed using compatible fabrication methods, making the possibility of using the same structures for both the accelerator and for these complementary beam manipulation devices highly attractive. With properly designed defect size and boundary conditions, TM accelerating modes as well as dipole and quadrupole modes exist for electron acceleration, focusing, deflection, and beam position detection. Due to the high damage fluence of dielectric materials at optical to IR wavelengths, the resultant field strengths in such devices can exceed those of more traditional RF and magnetostatic devices by 1 to 2 orders of magnitude.

Several DLA topologies [4, 5, 6] have been under recent investigation, as seen in Fig. 1: (a) a silicon woodpile photonic crystal waveguide, (b) a glass photonic bandgap (PBG) hollow-core optical fiber, and (c) a structure where the beam is accelerated by a transversely incident laser beam in the gap between two gratings. Significant progress has been made in the fabrication of prototypes of these structures with geometries optimized for accelerator use, as seen in the bottom images [7, 8, 9]. As seen in (a) 9-layer half woodpile structures have been successfully bonded to produce testable prototypes for 3.5 μm wavelength operation. Bonded fused silica prototypes of the grating structure shown in (c) have recently been completed, optimized for 800nm laser operation, and are currently undergoing beam testing, as discussed below. In addition, an alternate fabrication technique for larger period (9 μm wavelength) woodpile geometries is being explored in collaboration with Purdue University using a membrane stacking technique, as shown in Fig. 2(a).

Obtaining wall-plug efficiencies suitable for linear collider applications will additionally require the development of integrated couplers with high efficiency, fed by a network of waveguides that split the laser power from a common feed among various accelerator components. Initial results in simulating such couplers for the woodpile structure using silicon-on-insulator (SOI) waveguides indicate coupling efficiencies from the input waveguide to the accelerating mode close to 100% [10]. A prototype of this side coupling scheme has been integrated into the woodpile structure of Fig. 1(a), the result of which is shown in cross-section in Fig. 2(b). The power distribution scheme is then envisioned as a fiber-to-SOI coupler that brings a pulse from an external fiber laser onto the integrated chip, distributes it between multiple structures via SOI power splitters, and then recombines the spent laser pulse and extracts it from the chip via a mirror-image SOI-to-fiber output coupler [11], after which the power is either dumped, or for optimal efficiency, recycled [1]. Maintaining phase synchronicity of the laser pulse and the accelerated electrons between many separately fed structures would be accomplished by fabricating the requisite phase delays into the lengths of the waveguide feeds. Prototype grating to SOI couplers have recently been produced for 1.7 μm wavelength operation, images of which are shown in Fig. 2(c).

Power handling tests of these structures are planned to take place later this year.

Analytical calculations of the modes in the dual-grating geometry of Fig. 1(c) have recently been published by Plettner and Byer [12]. By selective phasing of two coincident laser pulses propagating in opposite directions perpendicular to the grating surfaces, it is proposed that modes with either accelerating, deflecting, or focusing properties may be excited in the gap region between the gratings. Simulations of a variant of the focusing scenario have been independently produced by Soong [13], indicating a maximal quadrupole gradient of 400 kT/m for a glass structure driven at 800nm wavelength. Focusing elements of this strength less than 100 microns in length would be adequate to confine a beam to the vacuum channel of a DLA accelerating structure in a linear collider scenario. Similarly, dipole modes in these or other structures, with appropriately designed input and output couplers, could be used to make micron-scale beam position monitors (BPMs) and steering elements. A concept for a BPM using a variant of the grating structure was also recently proposed by Soong [14]. The concept uses a dual-grating with a tapered grating period to produce a linear variation in operating wavelength along the dimension transverse to the beam axis. Light emitted by wakefield excitation by the electron beam (via the inverse of the acceleration process) would then have a different center wavelength depending on transverse position of the electrons, permitting a measurement of beam position from the power spectrum of emitted light.

BENCH TOP TESTING AND EVALUATION OF DIELECTRIC MATERIALS

The commercial photonic crystal fibers used in the wakefield experiments have also been used to measure phase stability and TM mode excitation with a table top CW laser. Due to their geometrical and compositional similarity to the accelerator structures of Fig. 1(b), these fibers are excellent stand-in devices to develop techniques for characterizing photonic crystal accelerator structures. Phase shift as a function of fiber temperature has been measured for the HC-633 fiber using a Mach Zehnder interferometer [15]. The measured phase dependence of 9 ppm/C corresponds to 3 degrees of phase shift per C over a structure 1000 wavelengths long, which is comparable to traditional RF accelerators. Furthermore, although they are designed for TE mode telecom use, TM modes have been successfully excited in these fibers by end-coupling a TEM01* laser mode generated using an ArcOptix liquid crystal mode converter [19].

In addition, extensive laser damage studies have been performed on a variety of optical materials in order to evaluate their suitability as base materials for fabrication of high-gradient accelerators. These measurements employed a pump-probe configuration where the decrease in specular reflection of a HeNe probe laser coincident with a pulsed IR laser on the sample provides a metric for the onset of damage to the material. A variety of common and exotic materials, including silicon, silica, and oxides of aluminum, zirconium, yttrium, and halfnium have been studied [20]. The damage fluence of patterned silica gratings, corresponding to those of Fig. 1(c), was found to be 1.7 J/cm^2 at λ = 800nm (half the damage fluence for bulk silica). When focused to a channel of width λ, this corresponds to approximately 2 GV/m peak electric fields. Assuming a ratio of 1/2 for the axial to peak field in a silica accelerating structure at this wavelength we obtain an estimate of 1GV/m on achievable gradient.

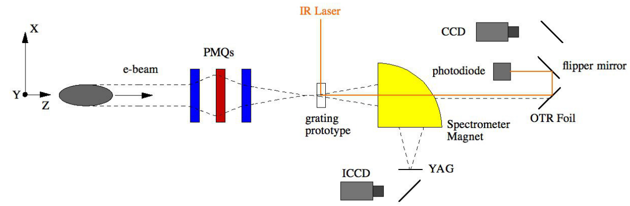

Figure 3: Schematic of laser-driven energy modulation experiment, using imaging spectrometer optical transition radiation (OTR) foil for gross timing overlap of electron and laser beams.

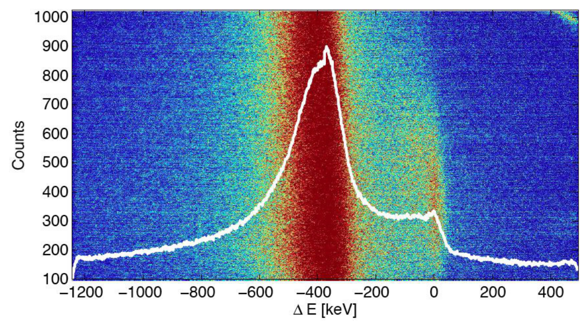

Figure 4: Example energy spectrum of the NLCTA test beam after passing through an unpowered 1.2 μm DLA grating structure, superimposed upon the raw image data.

BEAM BASED TESTING AND DEMONSTRATION EXPERIMENTS

Powered electron beam testing is currently underway using the pre-accelerated 60 MeV beam provided by the Next Linear Collider Test Accelerator at SLAC. Initial electron beam demonstrations are currently in progress using the dual-grating structure of Fig. 1(c), designed for 800 nm wavelength operation and with beam channel widths of either 0.8 or 1.2 μm in the vertical dimension, 1 mm in the horizontal, and 900nm in length along the beam axis. A schematic of the current experimental setup is shown in Fig. 3. The NLCTA test beam is focused with a triplet of permanent magnet quadrupoles into the prototype grating DLA structure, with typical RMS spot sizes of order 20 μm. After passing through the sample, the energy spectrum of the beam is analyzed with an imaging spectrometer and intensified camera (model PI-MAX3 from Princeton Instruments). Due to the small angular acceptance, most of the electrons impinge upon the silica substrate. By careful positioning of the structure, using 40 nm precision in-vacuum stages with 4 axes of control (2 transverse coordinates, and two angular degrees of freedom), a small population (approximately 1 to 7% of the particles that reach the spectrometer screen) has been observed to transmit through the accelerating channel. Due to collisional losses in the silica, the scattered and transmitted populations are separated in energy as seen in Fig. 4. The figure shows a spectrometer camera image with superimposed offset ΔE from the 60 MeV design energy, for a grating with 1.2 μm aperture. The large peak at $\Delta E = -400$ keV corresponds to particles downgraded in energy due to collisional losses. The distribution extending to the right of this corresponds to particles that travel partially through the substrate material and partially through the vacuum channel, with a hard-edged drop at $\Delta E = 0$ corresponding to full beam energy.

For laser-powered demonstration experiments, the 1ps electron and IR laser pulse lengths are long compared with the wavelength of the accelerating fields in the structure ($\lambda = 800$nm). Since the electrons will see all phases of the accelerating field, acceleration is expected to produce a modulation of the vacuum-transmitted particle energies, manifesting as a broadening of the sharp higher energy ($\Delta E = 0$) edge of the distribution in Fig. 4. Powered laser-on experiments are currently awaiting availability of the NLCTA IR laser amplifier following repairs to the pump laser. Gross timing overlap between the electron beam and the IR laser pulse is accomplished by turning off the spectrometer magnet and co-propagating both beams to an optical transition radiation (OTR) foil observed by a fast photodiode (50ps rise time), as seen in Fig. 3. Fine timing overlap at the 1ps level will be done by using the acceleration interaction signal itself to cross-correlate while scanning a fast delay stage on the laser line.

CONCLUSION

The electron beam tests will include other designs as test-ready prototypes become available within the current year. Designs for deflecting and focusing elements will be largely informed by the accelerator R&D, with beam tests for these structures occurring in future studies. Due to the strict emittance requirements for particle transmission through a micron-scale beam channel, indicated in Fig. 4, normalized emittances of 2 μm or less are desirable for the next stage of net acceleration experiments; and nanometer-scale emittances are required for future multiple stage acceleration schemes. Despite an order-of-magnitude reduction in beam emittance recently achieved through concerted beam studies and upgrades, typical normalized transverse emittance in the experimental section is 10 μm. In case the NLCTA test facility cannot meet the required beam parameters, we are considering two alternate routes: (1) development of low-emittance low-charge super-tip emitters through collaboration with MPI, where rapid progress is being made in development of such sources; (2) development of a SEM-based source. In both cases, the source electron energies will be of order 10's to 100's of keV, requiring new structure designs for phase velocities less than the speed of light.

REFERENCES

[1] R. H. Siemann. "Energy efficiency of laser driven, structure based accelerators", Phys. Rev. ST-AB, 7:061303, 2004.

[2] C. M. S. Sears and et al. "Production and characterization of attosecond electron bunch trains", Phys. Rev. ST-AB, 11:061301, 2008.

[3] P. Hommelhoff, Y. Sortais, A. Aghajani-Talesh, and M. A. Kasevich. "Field Emission Tip as a Nanometer Source of Free Electron Femtosecond Pulses", Phys. Rev. Lett., 96:077401, 2006.

[4] B. M. Cowan. "Three-dimensional dielectric photonic crystal structures for laser-driven acceleration", Phys. Rev. ST-AB, 11:011301, 2008.

[5] X. E. Lin. "Photonic band gap fiber accelerator", Phys. Rev. ST-AB, 4:051301, 2001.

[6] T. Plettner, P. P. Lu, and R. L. Byer. "Proposed few-optical cycle laser-driven particle accelerator structure", Phys. Rev. ST-AB, 9:111301, 2006.

[7] C. McGuinness, E. R. Colby, R. J. England, and et al. "Fabrication and measurements of a silicon woodpile accelerator structure", In 2011 Particle Accelerator Conference Proceedings, page 343, New York, NY, 2011.

[8] J. E. Spencer and et al. "Coupler studies for pbg fiber accelerators", In 2011 Particle Accelerator Conference Proceedings, page 346, New York, NY, 2011.

[9] E. A. Peralta, R. L. Byer, E. R. Colby, R. J. England, C. McGuinness, and K. Soong. "Fabrication and measurement of dual layer silica grating structures for direct laser acceleration", In 2011 Particle Accelerator Conference Proceedings, page 280, New York, NY, 2011.

[10] Z. Wu, E. R. Colby, C. McGuinness, and C-K. Ng. "Design of on-chip power transport and coupling components for a silicon woodpile accelerator", In 2011 Particle Accelerator Conference Proceedings, page 241, New York, NY, 2011.

[11] E. R. Colby, R. J. England, and R. J. Noble. "A laser-driven linear collider: Sample machine parameters and configuration", In 2011 Particle Accelerator Conference Proceedings, page 262, New York, NY, 2011.

[12] T. Plettner, R. L. Byer, and B. Montazeri. "Electromagnetic forces in the vacuum region of laser-driven layered grating structures", J. Mod. Opt., 58:1518, 2011.

[13] K. Soong, E. R. Colby, C. McGuinness, R. L. Byer, and E. A. Peralta. "Experimental determination of damage threshold characteristics of ir compatible optical materials", In 2011 Particle Accelerator Conference Proceedings, page 277, New York, NY, 2011.

[14] K. Soong and R. L. Byer. "Design of a subnanometer resolution beam position monitor for dielectric laser accelerators", Optics Letters, 37:975–977, 2012.

[15] R. Laouar, E. R. Colby, R. J. England, and R. J. Noble. "Measurement of thermal dependencies of pbg fiber properties", In 2011 Particle Accelerator Conference Proceedings, page 1343, New York, NY, 2011.