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FABRICATION AND DEMONSTRATION OF A SILICON BURIED GRATING ACCELERATOR

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Abstract

Using optical electromagnetic fields in dielectric microstructures, we can realize higher-energy accelerator systems in a more compact, low-cost form than the current state-of-the-art. Dielectric, laser-driven accelerators (DLA) have recently been demonstrated using fused silica structures to achieve about an order-of-magnitude increase in accelerating gradient over conventional RF structures. We leverage higher damage thresholds of silicon over metals and extensive micromachining capability to fabricate structures capable of electron acceleration. Our monolithic structure, the buried grating, consists of a grating formed on either side of a long channel via a deep reactive ion etch (DRIE). The grating imposes a phase profile on an incoming laser pulse such that an electron experiences a net change in energy over the course of each optical cycle. This results in acceleration (or deceleration) as electrons travel down the channel. We have designed and fabricated such structures and begun testing at the SLAC National Accelerator Laboratory. We report on the progress toward demonstration of acceleration in these structures driven at 2 um wavelength.

INTRODUCTION

Dielectric laser-driven accelerators (DLA) hold promise as an advanced accelerator technology capable of reducing system size and cost. Dielectric materials can have significantly higher damage thresholds at optical wavelengths than metals, allowing for the generation of close to 100 times greater acceleration gradients, in the GV/m range [1]. This, combined with the smaller structure, matched to optical wavelengths at the micron or submicron scale, in principle can drive the miniaturization of accelerator systems. By leveraging decades of photolithography and micromachining technology development, these types of structures can be produced on a large scale for relatively small cost. Driving with commercially available lasers rather that klystrons compounds these size and cost benefits.

Several dielectric accelerator structures have been proposed [2–5], but the grating accelerator [6] is the most successfully demonstrated to date. Subrelativistic electrons have been accelerated in fused silica and silicon Smith-Purcell gratings [7, 8] and relativistic electron acceleration has been demonstrated in a fused silica dual grating structure [9]. A silicon grating-based structure for the acceleration of relativisitic electrons, the buried grating, has also been proposed [10].

Grating DLAs use a laser incident normal to an electron beam with the field polarized in the direction of electron motion. The phase front of the laser is modulated by the grating and then incident on the electron beam travels through vacuum near the grating. This modulated phase breaks the temporal symmetry of a planar wavefront and results in a net acceleration or deceleration, depending on the position of the electron along a grating period. Short-pulse lasers are used to achieve high peak fields in the structure, and therefore high accelerating gradients.

Here we present the progress made toward demonstration of the silicon buried grating structure proposed in [10].

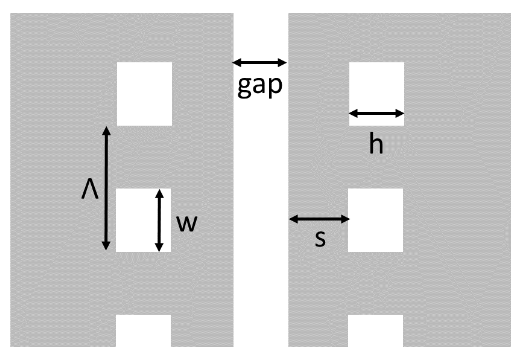

Figure 1: Illustration of parameters used in the design and simulation of buried grating structures.

DESIGN AND FABRICATION

Like previously demonstrated grating DLAs, the buried grating consists a phase grating adjacent to a vacuum region. The grating period is chosen such that the longitudinal component of the field (in the direction of electron travel) always produces an acceleration force. For phase matching the alternating acceleration field, we want the electron to traverse one grating period in one optical cycle, leading to the condition on the grating period of

$$\Lambda = \beta\lambda \tag{1}$$

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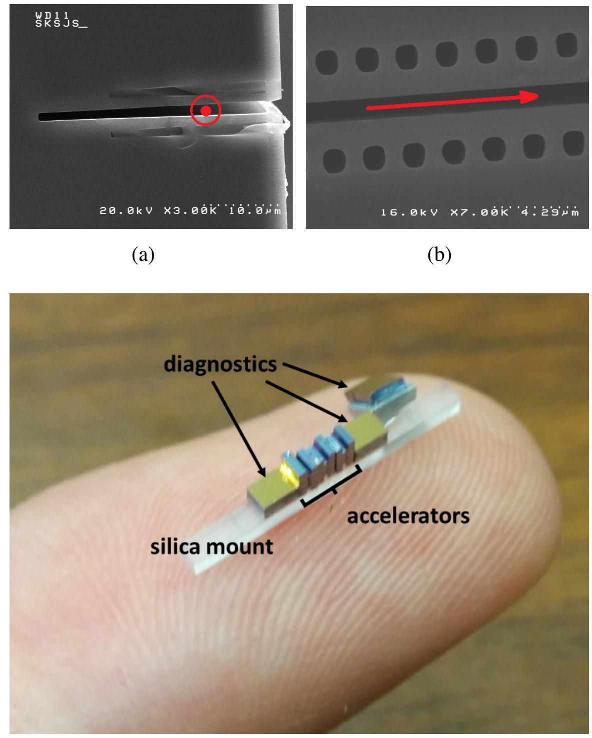
where λ is the driving laser wavelength, and β is the relativistic beta. As described below, we will be using a relativistic electron beam with $\beta \approx 1$, allowing us to simply equate the grating period to the driving wavelength. In order to achieve the proper phase shift during each half optical cycle we target a grating height of given by the path length difference between silicon and air that results in a pi phase shift

$$h = \frac{\lambda}{2(n-1)} \tag{2}$$

These are starting points for search of the possible parameter space which are verified using simulation to determine an optimal structure for acceleration.

The buried gratings are fabricated using standard micromachining techniques. The processing begins with a thermal oxidation of a silicon substrate and photolithography to define the buried grating. The oxide mask is etched in a CHF_3/O_2 chemistry and the accelerator structure itself is etched into the silicon via Bosch process deep reactive ion etch (DRIE). The oxide is stripped and a layer of LPCVD oxide is deposited as a mask for the second layer of lithography so as to not change the size of the etched grating holes. The second layer is etched with another combination of oxide RIE and silicon DRIE to create alignment features. Finally, the sample is annealed in a hydrogen ambient to reflow the etched silicon surfaces and eliminate scalloping from the DRIE. Individual die are cut from the wafer and mounted on a glass substrate for mounting on our sample stage. They are mounted with a blank cap die to seal off the top of the structure and prevent electrons from leaking over the top of the sample during testing. Images of the structures and mounted samples can be seen in fig. 2



(a) (b) (c)

Figure 2: Views of fabricated accelerator structures before hydrogen annealing, red markers indicates axis of electron travel: (a) view from upstream, electrons travel through the vacuum gap in the center (b) top view onto the surface of a etched buried grating (c) three accelerator samples mounted on glass substrate for testing with diagnostic structures for alignment and timing.

EXPERIMENTAL OVERVIEW

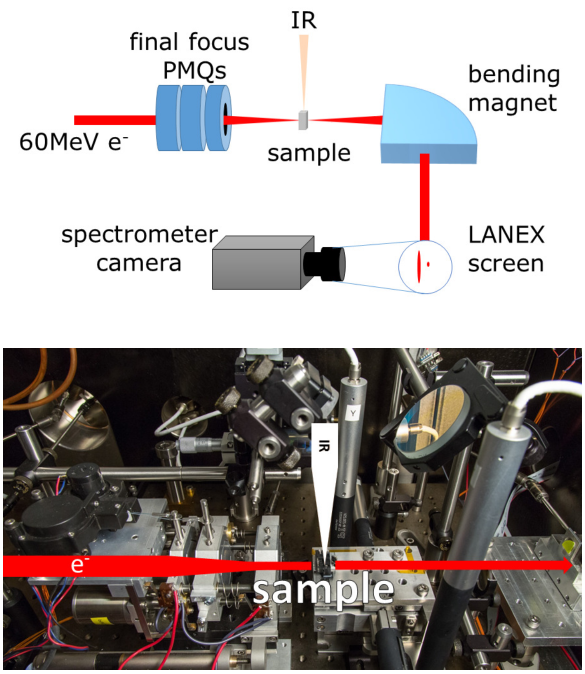
Testing of the silicon buried grating structures takes place at the Next Linear Collider Test Accelerator (NLCTA), a 120 MeV X-band beamline in the End Station B at SLAC National Accelerator Lab. The experimental facilities consist of the main beamline, the E163 experimental hall with the sample vacuum chamber, and the supporting laser facilities. The experimental chamber contains a four axis stage for moving the sample into position relative to the electron beam and optics to direct and focus the laser onto the sample. The laser used is the 2 μm output of a Light Conversion Topas optical parametric amplifier pumped by 800 nm pulses generated by a Coherent Legend Elite regenerative amplifier pumped by a Spectra Physics Tsunami Ti:sapphire oscillator.

As seen schematically in fig. 3, 1 ps pulses of 60 MeV electrons at 10Hz are transported to E163 experimental hall from a pickoff after the first of three linac sections. The electron beam is transported to our experimental chamber and focused onto the sample by a permanent magnet quadrupole triplet. After interaction of the electrons with 1 ps, 90 μJ optical pulses in the sample, they are transported through a bending magnet spectrometer and onto a LANEX phosphor screen. The energy spectrum is recorded with an intensified CCD camera. Figure 3(b) shows the actual setup in the experimental chamber.

STATUS AND FUTURE WORK

We have fabricated structures in silicon matched to a 2 μm drive laser and installed the 2 μm optics necessary for transporting as much energy to the sample as possible. Timing overlap has been performed to ensure that the electron pulses and laser pulses arrive at the sample to within several picoseconds of each other. Using a backreflected laser spot from the sample, we are able to ensure that the laser is incident perpendicular to the electron beam. We have achieved significant transmission of the electron beam through the vacuum channel with an aspect ratio of 1000:1. Experiments seeking observable signs of acceleration are in progress.

To date, results from other experiments have only shown modulation of electron energies due to the fact that electrons are distributed spatially along all phases of the grating. This leads to part of the measured populations gaining energy and part of them losing energy. We expect to observe this as an increase in the width of the transmitted peak in the energy spectrum as previously demonstrated in silica structures



(b) courtesy of SLAC/E163

Figure 3: (a) Schematic showing important part of the experimental setup, including electron beam final focus, interaction point located at the silicon sample, and spectrometer with detector setup (b) Photo of the experimental chamber showing the sample stage and electron and laser beam paths to the sample.

[9]. Electromagnetic field simulations suggest that with our fabricated structures we can achieve gradients approaching 100 MeV/m. This type of structure should in theory be able to produce a GeV/m scale acceleration gradient with a laser of sufficiently short pulse length [10].

Current and future experiments are aimed at testing accelerator structures with relativistic electron beams at NLCTA and non-relativistic beams in labs at Stanford. A full accelerator will need to be significantly longer than those that are so far fabricated. Thus, a useful accelerator based on these structures requires additional types of elements to guide and condition the beam over longer distances, and to deliver the laser to the structure in a controlled fashion. Toward that end, we also hope to demonstrate deflection and focusing structures based on similar principles and have begun investigating design of dielectric, laser-driven undulators for integration into a miniaturized DLA-based FEL system.

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REFERENCES

[1] K. Soong et al., "Laser damage threshold measurements of optical materials for direct laser accelerators", AIP Conf. Proc. 1507, 511 (2012).

[2] X.E. Lin et al., "Photonic band gap fiber accelerator", Phys. Rev. ST Accel. Beams 4, 051301 (2001).

[3] J. McNeur et al., "An Examination of Resonance, Acceleration, and Particle Dynamics in the Micro-Accelerator Platform", AIP Conf. Proc. 1299, 427 (2010).

[4] B. Naranjo et al., "Photonic laser-driven accelerator for GALAXIE", AIP Conf. Proc. 1507, 488 (2012).

[5] B.M. Cowan, "Three-dimensional dielectric photonic crystal structures for laser-driven acceleration", Phys. Rev. ST Accel. Beams 11, 011301 (2008).

[6] T. Plettner et al., "Proposed few-optical cycle laser-driven particle accelerator structure" Phys. Rev. ST Accel. Beams 9, 111301 (2006).

[7] K.J. Leedle et al., "Laser acceleration and deflection of 96.3 keV electrons with a silicon dielectric structure", Optica 2, 158 (2015).

[8] J. Breuer, P. Hommelhoff, "Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure", PRL 111, 134803 (2013).

[9] E.A. Peralta et al., "Demonstration of electron acceleration in a laser-driven dielectric microstructure", Nature 503, 91 (2013).

[10] C.M. Chang, O. Solgaard, "Silicon buried gratings for dielectric laser electron accelerators" APL, 104, 184102 (2014).