TOWARDS A FULLY INTEGRATED ACCELERATOR ON A CHIP: DIELECTRIC LASER ACCELERATION (DLA) FROM THE SOURCE TO RELATIVISTIC ELECTRONS*

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Abstract

Dielectric laser acceleration has recently demonstrated significantly higher accelerating gradients than radiofrequency structure-based accelerators. Towards the development of an integrated 1 MeV electron accelerator based on dielectric laser accelerator technologies, development in several relevant technologies is needed. In this work, recent developments on electron sources, bunching, accelerating, focussing, deflecting and laser coupling structures are reported. With an eye to the near future, components required for a 1 MeV tabletop accelerator producing sub-femtosecond electron bunches are outlined.

INTRODUCTION

Dielectric Laser Accelerators (DLAs) are electron linear accelerators composed of dielectric microstructures powered by pulsed infrared lasers [1–3]. Peak electric fields of ultrafast femtosecond infrared lasers are orders of magnitude above the damage threshold of metals, motivating dielectrics as the material of choice for the structure [4]. Significant progress in the field of DLAs has been made since the initial experimental demonstrations of accelerating structures [5, 6], with the highest accelerating gradient observed to date of 690 MeV m^{-1} [7]. The accelerating gradient limited by the material damage threshold is believed to exceed $\sim$1 GV m^{-1}, which would enable compact accelerators. In addition, beams produced by such devices would have unique desirable characteristics, in particular sub-femtosecond electron bunch lengths.

A desirable goal of research in this field to demonstrate acceleration of electrons from rest to relativistic energy. This requires the development, demonstration and subsequent integration of numerous particle accelerator technologies into wafer-scale dielectric devices [8]. In this work, we consider technological developments needed in order to realise a tabletop-scale demonstration of dielectric laser acceleration of sub-femtosecond electron bunches to $\sim$1 MeV. We outline recent technological developments of relevant components, and project possible technology choices for an integrated accelerator.

ELECTRON SOURCES

One aspect of DLAs that is significantly different from radiofrequency (rf) accelerator structures is that the transverse aperture of the accelerating structure is on the order of $\sim$1 μm. Passing a significant fraction of incident current necessitates electron sources producing beams with ultralow normalised transverse emittances on the order of nm rad.

Electron microscope tip sources in direct-current (DC) thermal emission electron guns have been usefully employed in DLA experiments [6, 9–11]. A desirable feature of such sources is their low electron energy spread (< 10 eV), and high energy stability. However the stochastic emission in time of electrons leads to very small electron-laser interaction probability at the DLA. Hence detection of accelerated electrons has been accomplished by integrating over many laser pulses.

Metal nanotip sources in DC photocathode electron sources have been demonstrated to emit femtosecond electron bunches with ultralow transverse emittances [12–15]. One aspect of these sources that is especially significant is that the effective source size has been demonstrated to be smaller than the radius of curvature of the nanotip itself [12].

Nanodiamond tips are a new type of electron source that is under consideration. Such sources have been shown to produce low transverse emittance beams under field emission. New research aims to additionally characterise the emittance of photoemitted electrons, for use as an electron gun [16].

In order to characterise various nanotip sources, an emittance diagnostic has been developed [17]. Using electrostatic focussing, the transverse distribution of emitted electrons is imaged at a downstream screen.

In parallel to the development of integrated ultralow emittance sources, access to conventional ultralow emittance sources is needed for experiments to test DLA structures. Conventional rf flat photocathode sources produce high-brightness relativistic beams of electrons [18], which can be compressed using velocity bunching to a longitudinal waist of <10 fs [19]. This is well-matched to the bucket duration of a 2 μm laser (6.7 fs). Simulations have shown that such sources could be implemented with an accelerator lattice including skew quadrupole magnets in order to produce 'ribbon' electron beams with a high transverse emittance ratio [20]. Such a transverse beam distribution would be well matched to the slab-geometry DLA transverse aperture.

ACCELERATING STRUCTURES

DLA accelerating structures that have been experimentally demonstrated were based on transverse-illuminated single and and dual-grating geometries [21, 22]. These grating geometries have been demonstrated to be fabricable using existing electron and ultraviolet (UV) lithographic techniques.

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Various geometry optimisations of accelerating structures have been experimentally demonstrated. Of particular note was the first demonstration of acceleration using a silicon microstructure [9]. Although the ultrafast laser damage threshold of silicon is significantly lower than fused silica in the near-mid infrared portion of the electromagnetic spectrum, the ready availability of micro and nano fabrication techniques makes this a highly desirable material. Rapid prototyping using electron beam lithography has subsequently enabled a variety of laser-driven experiments based on silicon microstructures [10, 23–26].

The laser damage threshold of DLAs powered by picosecond pulses was predicated on assumptions about damage threshold of dielectrics exposed to ultrafast laser pulses [27, 28]. The proposed mechanism controlling the single-pulse damage threshold was the Keldysh effect. This has been tested with ultrafast ps and fs duration pulses, and recently with few-cycle laser pulses [25]. However, as the pulse duration is shortened to fs, the high peak field of the laser pulse in the dielectric can give rise to self-phase modulation and self-focussing. This results in phase distortion of the pulse in the substrate material supporting the DLA. This becomes a signficant limitation to the maximum energy gain of electrons in a DLA, even below the material damage threshold [29]. However, since the function of the DLA depends on the presence of the pillars and not the substrate, the substrate can be removed [30–32]. Acceleration of electrons using a dual pillar structure has recently been experimentally demonstrated [10].

LONGITUDINAL BUNCHING

A longitudinal buncher will be required in order to accommodate electron sources with a bunch duration longer than an optical cycle. Two main techniques for bunching are considered.

At relativistic energies, the inverse free-electron laser (IFEL) is an interaction leading to longitudinal microbunching [33, 34]. While this has previously been demonstrated with dielectric surfaces, there are plans to demonstrate this microbunching at DLAs [35].

However for the application of bunching subrelativistic beams, velocity bunching is more appropriate. A technique to achieve longitudinal bunching (and net acceleration of charge) is proposed through the use of a longitudinally chirped accelerating structure [36]. The net acceleration of charge occurs because the longitudinal symmetry of the structure is broken by the period chirp.

Beyond a buncher structure, phase synchronous acceleration of subrelativistic electrons has been demonstrated by progressively chirping the structure period for a constant central laser wavelength [23, 37]. This enables the use of a single fixed central laser wavelength. This will be an especially important design optimisation for acceleration of subrelativistic electrons.

TRANSVERSE FOCUSSING

The accelerating modes at a DLA structure occur within less than an optical wavelength of the structure. Ballistic transport of electrons through an aperture without focussing results in significant reduction in beam current. As such, in addition to generating beams with low transverse emittance, a transverse focussing scheme is required to propagate beams while preserving ultralow transverse emittance from the source.

As an intermediate step, several macroscopic (mm-scale) focussing structures have been investigated. Permanent magnet [38] and microelectromechanical system (MEMS) quadrupoles [39] could be useful in demonstration experiments.

Several laser-driven focussing schemes have been proposed. A dual-grating structure illuminated by two beams from above and below [22, 40]. A transverse focussing structure has been experimentally demonstrated with subrelativistic electron beams [23]. A 'checkerboard' structure illuminated by two beams was proposed [41]. The principal desirable feature of laser-driven focussing structures is that the focussing gradient is orders of magnitude larger than for conventional (magnetic) focussing elements, and meets the requirements for stable focussing of ultralow emittance electron beams in a DLA channel [20].

LASER POWER DELIVERY

An important optimisation for large-scale accelerators based on lasers is that exponential industrial demand has resulted in a corresponding exponential decrease in the cost of diode-pumped solid state lasers over time [42, 43].

Significant development of DLA structures is currently being undertaken assuming a 2 μm drive laser wavelength. This is intended to take advantage of projected industrialisation of Thulium and Holmium doped fibre amplifiers. As such, recently a 2 μm wavelength laser for DLA applications was demonstrated [44].

A desirable technique for laser pulse delivery to the DLA may be a hollow-core anti-resonant fibre [45]. Compression of a laser pulse using hollow-core fibres is possible, and would minimise the transport distance of a compressed pulse [46].

From the perspective of optimising laser power management, the development of photonic crystal structures closer to travelling wave structures would be desirable. An example is the woodpile photonic crystal lattice structure [47]. Experimental fabrication of woodpile lattice has been undertaken, however sub-wavelength feature alignment has been an obstacle precluding experiments with electron beams. A promising new fabrication technique is additive manufacturing [16]. The two-photon laser write technique has demonstrated a minimum fabricable feature size of $\sim$100 nm, which is sufficient for DLAs. In addition to the minimum feature size, such materials must also be demonstrated to have sufficient laser and radiation damage thresholds in an ultrahigh vacuum environment, as was demonstrated previously for dielectric materials [28, 48].

In order to power photonic crystal lattice structures, the power coupler is a critical design aspect [49–51]. As with the structure fabrication itself, novel additive manufacturing techniques may be beneficial to the alignment and fabrication of such couplers [16].

DIAGNOSTICS AND CONTROL

In order to control beams with nm dimensions, beam diagnostics with sensitivity at the ~nm scale will be required. Two schemes for beam position monitors have been demonstrated in recent years. A passive position monitor was demonstrated with relativistic electrons, based on a DLA grating structure with transverse chirp [52, 53]. Recently, an active beam position monitor was developed, powered by femtosecond laser pulses [24].

Once the electron beam trajectory is measured, it should be corrected using transverse deflecting structures. Recently, a phase-stable transverse deflecting structure has been demonstrated [23]. This also opens up the potential of transverse streaking of electrons as an application for lased-driven deflecting structures [26].

TABLETOP SCALE DEMONSTRATION

Considering the demonstrated readiness of individual components, we project forward into the future a few years to the requirements for a demonstration experiment of acceleration of electrons from rest to ~1 MeV in a tabletop-scale accelerator.

Electron Source

For a compact tabletop electron source, conventional DC photocathode sources have been demonstrated as useful sources of low transverse emittance electron beams for DLA experiments [54]. Such structures have minimal system requirements: principally DC high voltage, and ultrahigh vacuum. Typically the cathodes of such sources are triggered with a UV pulse, which could be a phase-locked frequency multiple of the infrared drive laser pulse. Electron acceleration at DLAs has been demonstrated with electron kinetic energies as low as 10 keV [15], which is a modest high voltage requirement for a tabletop source.

Bunching Structure

the nominal bunching structure would probably be a dual-pillar silicon microstructure operating at a high harmonic of the fundamental accelerating mode [15]. A high harmonic would be used so as to maintain the minimum feature size of the structure larger than the smallest fabricable feature size of order ~100 nm. The mode would be designed to reduce to the fundamental as the electron accelerates along the structure. The structure would be chirped in order to maintain synchronicity of the accelerating electrons with the accelerating mode [36].

In addition to the ease of fabrication afforded by choosing silicon as the material, the choice of a semiconductor rather than dielectric minimises damage to the surface from electrostatic charging from low-energy scattered electrons striking the surface [9].

Accelerating Structure

Owing in large part to monolithic fabrication, the accelerating structure would probably be an optimised-geometry dual pillar structure [10]. This structure has the desirable effect of minimising the influence of nonlinear effects of the material on the drive laser pulse [29]. The structure would be powered by a pulse-front tilted laser beam.

The optimisation of structures may move away from nonresonant structures towards slightly resonant structures [55–59]. Through the inclusion of Bragg mirrors, such structures serve to modestly enhance the incident field perhaps by a factor of ~2−3. In addition, new simulation techniques may be used to design structures based on additional metrics than the peak accelerating gradient [60].

Focussing Structure

Macroscopic permanent and electromagnetic quadrupole lenses with transverse focussing gradients of ~kT m^{-1} [38, 39] may transport electron beams through a small number of acceleration stages in a first tabletop demonstration device. In order to adequately focus an electron beam within a ~μm gap, the lens must be of order ~mm in length. This would be acceptable for a tabletop accelerator optimised towards the generation of ultrashort electron bunches rather than maximum average accelerating gradient.

With transverse focussing gradients of ~kT m^{-1}, such magnetic structures may not be appropriate for an accelerator optimised for high energy. Hence, in the longer term, a laser-driven focussing structure is needed in order to achieve focussing gradients needed to confine beams within the DLA aperture [20].

While electromagnetic simulations of extended structures are possible using supercomputers [7, 61], modelling the effect of focussing structures on beams in extended DLA-based accelerator lattices is desired. Parameterisations of the solved field distribution evaluated in electromagnetic structure simulations may subsequently need to be incorporated in tracking simulations [62–65].

Laser Delivery

Previous and present DLA experiments have been powered by commercially available lasers. For a demonstration tabletop experiment, the laser source would probably be a regenerative amplifier and optical parametric amplifier (OPA) producing 2 μm light to power the accelerating and focussing structures. A UV pulse for the photocathode would also be provided by frequency multiplying a fraction of the original NIR pulse.

Ideally, laser power delivery would be integrated on-chip. For a first demonstration, it seems more likely that free-space optics would be used. In particular, laser power would probably be delivered to the bunching and accelerating structures using pulse-front tilted laser beams [21, 62].

In the event that additive manufacturing materials are not radiation tolerant and thus suitable for accelerator components themselves, such fabrication techniques might usefully employed in power couplers required to deliver laser power to the accelerating structure.

Diagnostics and Control

A demonstration device producing trains of electron microbunches necessitates some kind of longitudinal bunching diagnostic. Previously, microbunching at infrared wavelengths has been observed as an increase in power of coherent transition radiation [33].

Another possibility to measure the electron microbunch duration may be to streak the electron microbunches in the transverse direction, using a laser-driven deflecting structure [23, 26].

OUTLOOK

Crucial technologies needed to enable the development of linear accelerators based on DLAs presently exist and have been demonstrated in laboratory settings. Several key technologies need further development and demonstration, in particular focussing structures. Integration of these technologies into a tabletop-scale accelerator producing relativistic femtosecond electron bunches appears feasible in the near future.

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