EXPERIMENTAL PROGRESS TOWARDS A RESONANT SLAB-SYMMETRIC DIELECTRIC LASER ACCELERATOR*

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Abstract

The Micro Accelerator Platform (MAP), a resonant dielectric structure for laser acceleration of electrons, has been in development for a number of years. It consists of a vacuum gap between two slab-shaped reflecting boundaries, with a transmissive grating diffractive optic on one boundary that allows laser power to propagate into the gap and enforces an accelerating mode. We report on the progress of bench and beam tests carried out within the last year, and the challenges faced in diagnosing <pC beams from optical-scale structures. We also describe refinements to our fabrication techniques and lessons learned during the development of the fabrication process.

INTRODUCTION

Dielectric Laser Accelerators (DLAs) offer a potential path to high acceleration gradients, using structures that can be fabricated on the wafer-scale via methods developed for the microchip industry, and using fiber lasers which afford very high repetition rates in compact packages. These devices push beam parameters into a new regime: sub-fs, sub-μm and sub-pC bunches. The resultant demands on testing and diagnostics are challenging. Here we describe the efforts to build, characterize and test one such DLA—the Micro Accelerator Platform (MAP).

FABRICATION RESULTS

The MAP consists of a resonant optical cavity bounded above and below by Bragg reflectors (a stack of thin films, for fabrication purposes), with one reflector overlaid with a patterned coupling structure similar to a transmission grating. The details of the structure [1], simulations [2] and preliminary fabrication efforts [3] have been detailed elsewhere. Recent work has focused on producing consistent, high quality structures within design tolerances.

Fused silica was chosen as the fabrication substrate due to its high thermal and mechanical stability, and high optical transparency at the operating wavelength of 800 nm.

The Distributed Bragg Reflectors (DBRs) for the upper and lower slabs consist of alternating ZrO_2 and SiO_2 layers. Here we have used sputtering (using a Denton Discovery 550) to deposit the thin films. To obtain uniform thin films, the RF power for the sputtering system was optimized over several runs for each material. The thicknesses of the films were calibrated using a profilometer.

Figure 1 shows two samples of the upper DBR structure: a focused ion beam (FIB) cross-section was cut into the DBR and a scanning electron microscope (SEM) image was taken (using a FIE Nova 600) of each. As an example of the fabrication challenges faced, Fig. 1(a) shows a DBR that was fabricated after changes were made to the depositor. It was found that the deposition thickness of the thin films varied significantly from prior calibrations, and was eventually discovered to be mainly due to the temperature variation of the target. The thickness variation of ZrO_2 was more prominent than SiO_2 deposition. The un-calibrated DBR does not show 7 distinct layers and the thickness varies significantly between two consecutive depositions. Fig. 1(b) shows a DBR made after calibration of the machine, and indicates that the thicknesses are within the tolerance limit of ±10 nm from the desired thickness.

The coupling structure, which sits atop the upper DBR, consists of an array of filled slots in the outer surface and several underlying matching layers. Coupler slots (with slot width of 286 nm and period of 800 nm) filled with HfO_2 on SiO_2 thin films were fabricated in a two step process: first, using e-beam lithography, 90 nm thin HfO_2 slots were made on the fused silica substrate. Next, a thicker SiO_2 film was deposited atop the coupling slots. Polishing (CMP) was used to cutback the layer and expose the HfO_2 slots. The matching layers, consisting of alternating SiO_2 and HfO_2 thin films, were deposited in an e-beam evaporator system (CHA).

In order to form the gap between the slabs, SiO_2 spacers (800 nm height and 250 μm width) are formed on either side of the (200 μm wide) beam channel, using optical lithography, evaporation and lift-off.

The upper slab and the lower slab structure are then subjected to bonding. Fusion bonding (using a Karl-Suss SB6) was attempted several times, but the surface quality of the spacers and possibly the adhesion strength of the various films were too low to form permanent bonds.

Optimization continues on the bonding process, including methods to "activate" the surfaces, and bond temperature and pressure. Our experimental results show that increasing the bonding time or pre-annealing the thin films does not improve the bond strength. As an alternative to fusion bonding, a temporary bond using polymers is being evaluated.

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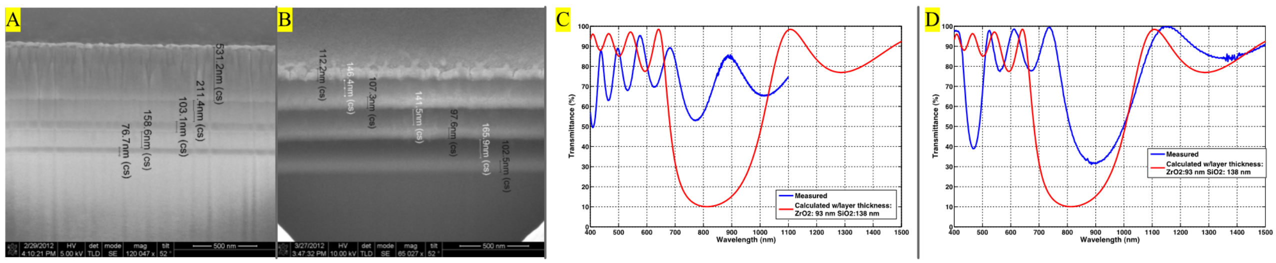

Figure 1: SEM micrographs of DBR cross-sections for the MAP structure upper slab: (a) before calibration of the deposition machine; (b) after. Comparison of transmittance measurements on structures (blue) and simulation using ideal dimensions (red): (c) for the structure labeled A; (d) for the structure labeled B.

Optical Structure Testing

While SEM micrographs as in Figs. 1(a),(b) provide a measure of the physical properties of the structure, the optical properties are of most relevance to the MAP. Transmission spectra of the slabs in the wavelength range 400–1500 nm were measured using a UV/Vis/NIR spectrophotometer (Shimadzu UV-3101 PC). Simulations predict that the wavelength and the bandwidth of the peaks are functions of layer thicknesses, refractive indices and the total number of layers.

For rapid comparison with measurements, the Macleod characteristic matrix method was used to calculate the ideal expected spectra. [4] This method makes use of a plane-wave-based iterative calculation of the characteristic matrix. A characteristic matrix can be calculated for each layer of thin film and a running multiplication for the multi-layer structure gives a final characteristic matrix that yields the transmission and reflection spectra of the total assembly. Absorption by the layers was neglected, but final comparisons of the measured spectra were benchmarked against HFSS simulations, which include losses.

Figure 1(c) shows the measured spectrum of the DBR fabricated prior to equipment re-calibration. In the figure, the narrower-than-expected bandwidth of the main peak indicates that the ratio of the refractive indices is too low. Additionally, the flattening of the main peak results from the presence of too few Bragg layers. Fig. 1(d) is a measurement of a 7-layer DBR after calibration; the calculated values use the ideal design thicknesses for silica of 173 nm and for zirconia of 90 nm. The expected and measured values match well; this agreement improves further when using as-built dimensions.

TRANSMISSION EXPERIMENTS

Beam testing of the MAP structure began with transmission tests of a uniform dummy structure with the correct aperture dimensions. Testing was conducted at SLAC's NLCTA/E163 facility.

Experimental Set-up

The E163 set-up provides a beam of 60 MeV, with minimum beam sizes of 10-20 µm at the focus of an adjustable permanent magnet quadrupole (PMQ) system contained within a ~meter-long vacuum box designed for precision placement of microstructures. The use of a high-resolution dipole bend-magnet spectrometer allows for the separation of particles that have lost energy through collision with the structure (or holder) from those particles that have traversed the vacuum gap. The spectrometer is also able to measure the change in the beam momentum as a function of the laser power applied to the structure.

Challenges

Alignment of the structure at the nanometer scale is often mentioned as a hurdle for DLA structures. However, piezoelectric positioners are able to place objects with a few nanometers of precision in 6D space. Knowledge of the structure location relative to other beamline objects, such as focusing magnets, is indeed a challenge.

One issue facing measurements of DLA performance is distinguishing the few particles that traverse the active area from the far larger population of particles which do not (Figure 2). As mentioned above, momentum separation is a useful tool for this segregation. In the case here, the incident beam is ~10 µm and the gap is ~1 µm (800 nm). For a 1 mm long structure, the energy loss (dE/dx) in glass is approximately 0.5 MeV for a 60 MeV incident beam. As the E163 spectrometer has a resolution of ~3 keV, separation of the two populations is straightforward. A remaining issue is maintaining an acceptable signal-to-noise (S/N) ratio, as the low-charge e-beam exists in the presence of ambient noise caused by stray particles, x-rays, RF, etc.

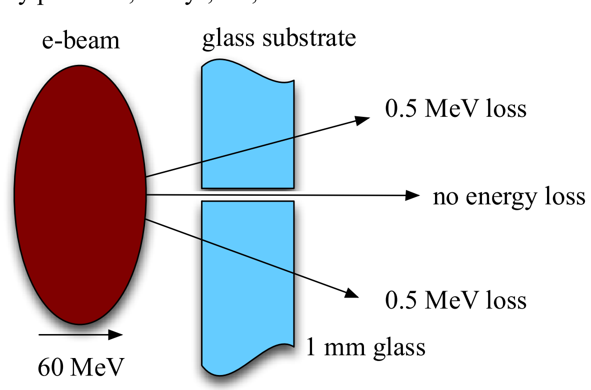

Figure 2: Transmission model of beam through structure.

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Simulation Results

In an effort to understand the quality of beam necessary to observe transmission through the MAP structure, a series of simulation runs were performed (using Elegant) in which the beam emittance and the distance of the PMQ triplet from the MAP were varied independently. For each point in this parameter space, the number of electrons that travelled through the 2 mm x 1 µm vacuum channel of the MAP was recorded, along with the spot size of the beam at the IP YAG. The number of electrons was converted to photons hitting the CCD by taking into account geometric and efficiency factors of the PI-MAX3 camera as well as the assumption that the photons emitted from the Ce:YAG can be space-compressed by a factor of 3 using a lens between the PI-MAX3 and the YAG. An estimate of the relevant noise (due to the beam, camera, and other factors) was calculated using spectrometer images from previous runs. S/N ratios derived from this information are presented in Fig. 3.

The simulation results indicate that adequate S/N ratios can be achieved for normalized y-emittances of 20 µm-rad or less and $\sigma_y \leq 20$ µm. An important lesson from this study is that the relative positioning of the PMQ stage and the MAP structure dramatically affects the S/N ratio. Changing the position of the PMQ stage by as little as 1 mm can change the transmitted signal by a factor of 3.

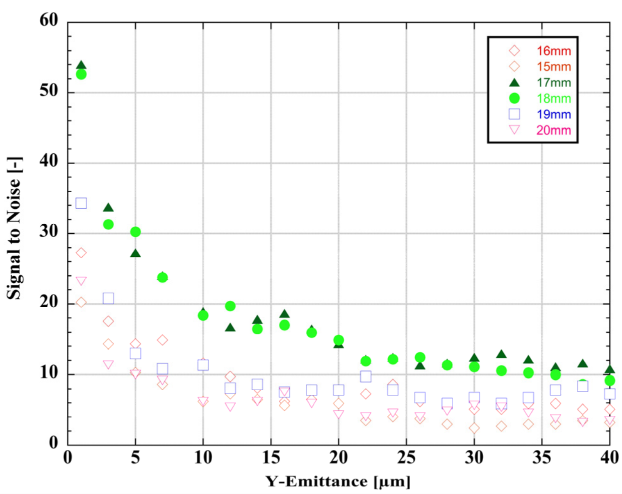

Figure 3: S/N of structure transmission from simulations.

Measurement Outcomes

Measurements of beam transmission through the dummy structure were hampered by atypically large beam emittance and significant jitter. Despite these issues, transmission through the structure was observed (Fig. 4).

With an incident electron spot size of approximately 96 µm x 83 µm, and emittances of 43 µm and 24 µm-rad, a small population of particles was observed at the injection beam energy, while a larger population was observed with a mean energy loss of 0.34 MeV (using a 1.776 KeV/pixel calibration). This energy loss is slightly lower than the expected value of 0.5 MeV inferred from the stopping power of the glass; the reason for the discrepancy remains uncertain but may involve geometric effects. Unpowered deceleration is not observed in these experiments, as the energy loss (about 0.5 MeV) due to wakefields would be roughly the same as the energy loss in glass.

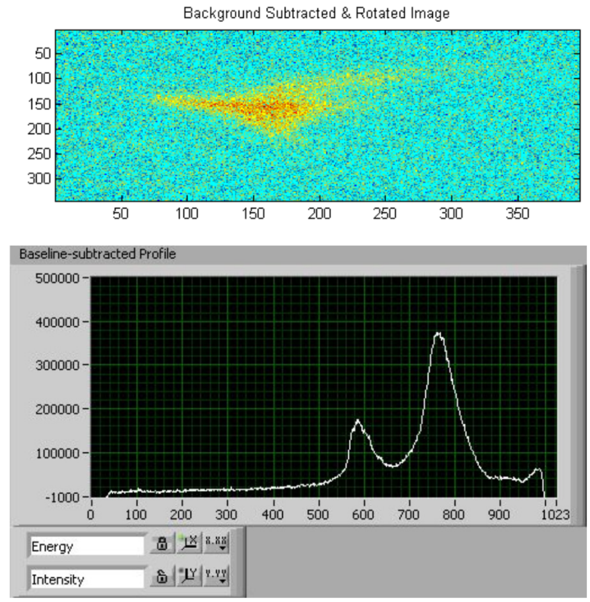

Figure 4: (top) Image from spectrometer camera; (bottom) Line-out of top image.

ACCELERATION EXPERIMENTS

Experimental acceleration studies of the MAP structure are ongoing. Efforts include fabrication of higher quality, well bonded and fully characterized structures. Pending improvements of beam quality at E163, combined with better control of the drive laser steering and optical size, are anticipated to lead to more reliable transmission and also allow powering the structure.

Acceleration of up to 1 MeV over the 1-mm-long structure is expected. However, as all phases of the structure are filled by the ~ few ps long electron beam, the average energy gain would be approximately half the peak, or 0.5 MeV.

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