TESTING OF A LASER-POWERED SLAB-SYMMETRIC DIELECTRIC STRUCTURE FOR MEDICAL AND INDUSTRIAL APPLICATIONS*

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Abstract

Laser-powered dielectric accelerating structures, which have attracted attention in recent years, trade fabrication challenges and extremely small beam apertures for the promise of high gradients and new bunch formats. The slab-symmetric, periodically-coupled Micro Accelerator Platform (MAP) is one such dielectric accelerator, and has been under development through a RadiaBeam-UCLA collaboration for several years. Intended applications of the structure include the production of radiation for medical treatments, imaging, and industrial uses. Prototype MAP structures are now being fabricated, and a program has been undertaken to test this device using externally injected electron beams. Plans are underway to install structures in the E163 facility at SLAC. In this paper we describe the testing methods, diagnostics and expectations. Progress and results to date are also presented.

INTRODUCTION

Low-energy relativistic electrons (1-10 MeV), and the X-rays they produce, are used in a host of applications within medicine, industry, and security. However such radiation sources have to date been generally produced by large, expensive RF accelerators. RadiaBeam, in collaboration with UCLA, is currently developing a micron-scale, laser-powered accelerator, which we call the Micro-Accelerator Platform (MAP). The core concept of the MAP is a dielectric slab structure powered transversely by a high peak power laser, which, when combined with an innovative particle source embedded at one end of the structure, will become a stand-alone radiation source. The structure geometry affords a straightforward means of tuning and coupling-in power, both of which are critical for a micron-scale device. The MAP is being designed as an inexpensive, disposable, particle source for commercial applications, such as radiation therapy and non-destructive testing.

The physics of the MAP have been developed over more than a decade at the UCLA Particle Beam Physics Lab. For more details about the design of the device, we refer the reader to past publications [1,2,3,4,5,6,7,8]. To summarize, the accelerating structure is a slab-symmetric dielectric-lined resonator. The slab-symmetry suppresses wakefields and thus beam breakup instabilities [2]. The use of a dielectric liner on either side of a vacuum gap means that the highest fields in the structure will tend to be at the vacuum/dielectric interface, and dielectric materials can withstand fields up to 1 GV/m for pulses of a few ps without breakdown [9, 10]. In addition to high gradients, a laser-driven slab-symmetric device can accelerate comparatively large amounts of beam charge without significant beam loading, since the charge is spread out across the wide transverse direction. Finally, the manufacturing of planar structures with sub-micron precision is enabled by semiconductor fabrication technology.

RadiaBeam has recently applied for Phase II SBIR funding to build and test a dielectric structure. In this paper we describe the design of the device and our plans for a proof-of-concept experiment at SLAC E163.

ALL-DIELECTRIC STRUCTURE DESIGN

We have designed an all-dielectric MAP structure for a proof-of-concept experiment. The structure was designed to accelerate externally injected, $\beta \approx 1$ electrons. This eliminates the complication of tapering the structure, and allows us to proceed with optimization of the basic design and fabrication processes while development is ongoing on the integrated electron source.

Early work on slab-symmetric accelerators used designs incorporating metal boundary walls, as in [5], on the exterior surfaces. Perfectly conducting boundaries greatly simplify the design and make it relatively easy to produce a strong resonance; however, in practice metals are lossy in the far infrared, and realistic metal-walled devices have poor performance at $\lambda \sim 1$ µm. An all-dielectric structure will function at any wavelength, assuming that absorption is not significant. In such a device, the conducting boundary mirrors forming the resonator are replaced by Bragg reflectors [11]. Coupling can no longer proceed via apertures in the mirrors, as power will no longer be channeled through the aperture but will preferentially fill the dielectric material. Therefore, we have developed and simulated a coupling mechanism for the all-dielectric structure, involving a diffractive element that shifts the phase of the incoming laser wavefront before allowing it to leak into the accelerating structure through the Bragg stack.

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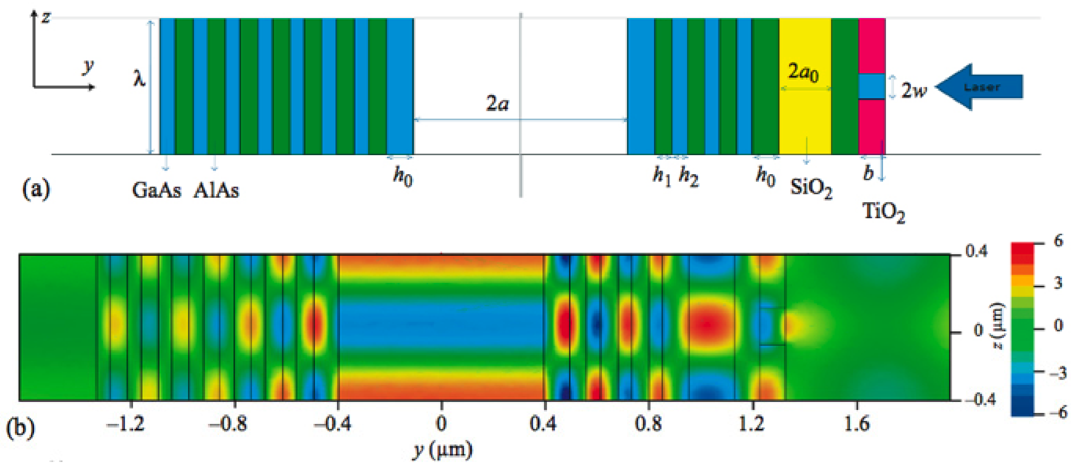

Figure 1: (a) Schematic showing the arrangement of layers and definition of parameters for one period of an all-dielectric structure. (b) False-color field map of Ez in this structure, normalized to amplitude of drive laser. (HFSS simulation). For this result, $h_0 = w = b = 100$ nm; $a = 400$ nm; $a_0 = 180$ nm; h_1 and h_2 are λ/4 Bragg layers.

Figure 1 shows the main features of the all-dielectric design, with sample simulation results for the resonant fields in this iteration of the device. The diffractive element on the outer surface consists of a periodic array of high-epsilon material, through which the laser fields are preferentially guided. Under this layer is a relatively thick layer of low-index material (with dimension $2a_0$ in the figure), the function of which is to enforce a phase delay between the coupler and the Bragg stack. The radiation then arrives at the Bragg stack having the correct phase relationship for coupling to the desired resonance, with fields at the center of the structure period (at $z = 0$ in the figure) 180° out of phase with those at $z = \pm 0.4$ μm. This phase relationship is unchanged as the fields leak through the Bragg stack.

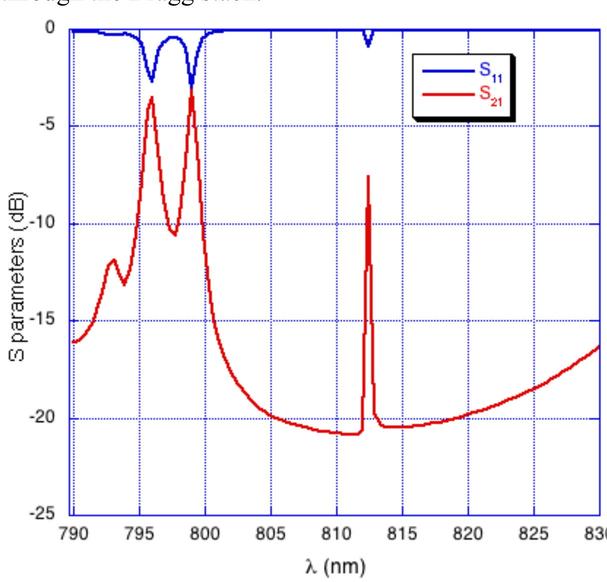

Figure 1: Simulated S_{11} and S_{21} for the dielectric structure. The desired accelerating mode is at 799.9 nm, with a weaker off-phase companion at 796.1 nm. The weak resonance at 812 nm is a non-accelerating mode.

Figure 1(b) shows that accelerating fields within the beam channel are roughly 5 times those of the drive laser, though it is obvious that comparable fields exist in part of the dielectric stack. Figure 2 shows simulated *S* parameters for this design, in which several structure modes are identified.

FABRICATION

The structure described above was originally designed using epitaxial growth compatible materials, including GaAs and AlAs. These materials afford very high efficiencies (very high reflectivity Bragg stacks) and the ability to create monolithic structures in opto-electronic devices (such as vertical-cavity surface-emitting laser diodes). For the MAP, these considerations are secondary, and the complexities encountered in using molecular beam epitaxy are not warranted. These considerations, as well as the aforementioned challenges in creating a hybrid epitaxial/dielectric structure, and our consultations with commercial foundries have led us to switch to an all-dielectric (nonepitaxial) structure. The dielectric layers themselves can be fabricated from a range of materials such as SiO2, SiOxNy, TiOx, AlOx, HfO2, ZrO2. These and other materials will be evaluated for optical and fabrication compatibility.

We have developed a viable plan for fabrication through discussions with commercial MEMS foundries. The substrate material will be silicon, as this allows the widest range of deposition and etching processes to be performed. Electron beam lithography will be used to produce the coupling slot pattern. The slots are filled in with the chosen dielectric material, and then the remaining dielectric layers are deposited using standard thin-film techniques. We are currently working with a commercial foundry to refine the fabrication process and chose the final dielectric materials to be used in the new design.

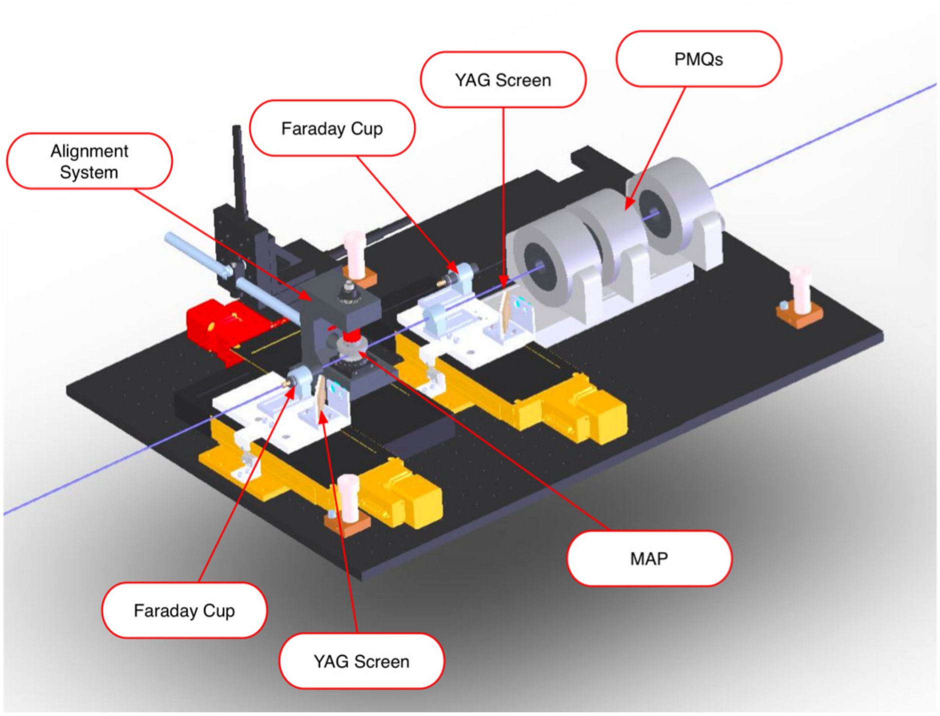

Figure 3: CAD rendering showing diagnostics and the alignment system.

TESTING

Once the design has been completed with the new dielectric materials, we will fabricate several prototype structures and perform bench testing to validate the quality of the fabrication process. The testing will utilize the procedure developed at UCLA, in which a fiber spectrometer is used to measure S11 and S21, and interferometer is used for alignment [12].

We will perform the proof-of-concept experiment at SLAC E163. The top and bottom slabs will be aligned in a custom fabricated mount using a piezoelectric nanopositioner, and placed into the E163 experimental chamber. Alignment to the beam will be performed with an in-vacuum micropositioning translation stage. A collimator and diagnostics have been designed to be placed into the chamber (see Figure 3). The beam will be injected into the structure using an existing permanent magnet quadrupole (PMQ) triplet. The E163 magnetic spectrometer will be used to observe accelerated electrons. We expect to observe 50 – 100 keV of acceleration of at least 0.1 pC, which is well within the resolution and sensitivity of the spectrometer.

SUMMARY

An all-dielectric, laser-powered slab-symmetric accelerating structure has been designed as a proof-of-concept device for a future commercial electron/X-ray source, and the fabrication process has been studied. We recently applied for funding to build the structure and perform initial acceleration experiments at the SLAC E163 facility.

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