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DESIGN OF ON-CHIP POWER TRANSPORT AND COUPLING COMPONENTS FOR A SILICON WOODPILE ACCELERATOR*

Z. Wu#, C. Ng, C. McGuinness and E. Colby, SLAC, Menlo Park, CA 94025, U.S.A.

Abstract

Three-dimensional woodpile photonic bandgap (PBG) waveguide enables high-gradient and efficient laser driven acceleration, while various accelerator components, including laser couplers, power transmission lines, woodpile accelerating and focusing waveguides, and energy recycling resonators, can be potentially integrated on a single monolithic structure via lithographic fabrications. This paper will present designs of this on-chip accelerator based on silicon-on-insulator (SOI) waveguide. Laser power is coupled from free-space or fiber into SOI waveguide by grating structures on the silicon surface, split into multiple channels to excite individual accelerator cells, and eventually gets merged into the power recycle pathway. Design and simulation results will be presented regarding various coupling components involved in this network.

INTRODUCTION

Laser driven dielectric PBG accelerating structures have drawn great interest due to the potential ~ GeV/m accelerating gradient and widely available high-power, high-efficiency lasers as driving sources [1]. The Woodpile structure in particular provides three dimensional EM field confinement and manipulation, and has been shown to exhibit TM-like modes in the defect waveguide to support electron acceleration [1, 2]. Individual rods in the structure discretize the spatial dielectric distribution; therefore offer required degrees of freedom for mode control and building various coupling and focusing elements. The structure, if made of silicon, could potentially be well suited into standard photolithography process, and fabricated on a single wafer as an on-chip accelerator.

Figure 1 shows the proposed layout of an on-chip accelerator. The chip consists of several accelerating cells with each cell formed by a woodpile defect waveguide structure, providing the electron beam accelerating channel as well as the coupling channel for laser power injection. As shown in the inset, the laser power coupler follows a side coupling design, where the photon input waveguide crosses the electron beam channel perpendicularly and ideally couples laser power into the fundamental accelerating mode along the e-beam channel in the forward direction. A single laser source may power the whole chip, given proper power transport and split lines as the blue routes in the layout represent. A power recycle loop may be necessary too to reuse the injected laser power for next electron acceleration, which greatly enhances the system efficiency [3]. The layout reflects various coupling components that need to be designed, including input laser to power line coupler, power splitter, power line to woodpile input waveguide coupler, and woodpile input waveguide to beam channel coupler. In the next section, elaboration will be given upon design of each of these coupling components.

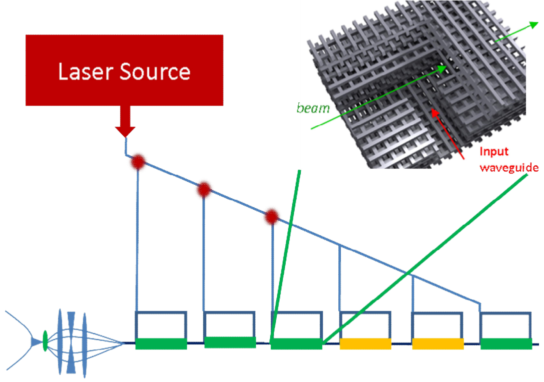

Figure 1: Layout of the on-chip woodpile accelerator.

COUPLING COMPONENTS

Design of the power line and coupling components takes into consideration the manufacture difficulty: they shall be practically manufacturable by standard nano-fabrication processes and involve commonly available materials. The design wavelength is the nominal 1.55 um telecom wavelength.

Silicon-on-Insulator Waveguide

The accelerator chip shall ideally be driven just below the damage threshold of the power line – presumably a dielectric waveguide – to offer as strong accelerating gradient as possible. Silica is a good candidate in that sense; however its relatively small dielectric constant contrast with respect to air leads to weak field confinement and difficulties in single mode operation and power splitter design. Silicon-on-insulator (SOI) waveguide is therefore chosen as the basic power transport line on the chip. The waveguide is simply a silicon slab sitting atop a lower-index substrate. Total internal reflection between silicon-air and silicon-substrate interfaces ensures the low-loss power guidance. For silicon-on-silica (SOS) case, the waveguide supports single TE-mode operation at 1.55 um wavelength as long as the silicon slab thickness is kept under ~300 nm. The slab width can therefore be large to spread the laser field intensity and keep it under the silicon damage fluence value. The left figure in Fig. 2 depicts the *x*-polarized fundamental TE mode in a 220 nm thick, 1 um wide SOS waveguide, simulated using Ansoft HFSS v12 [4]. The simulated model is one half of the practical waveguide by

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#wzr@slac.stanford.edu

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SLAC National Accelerator Laboratory, Menlo Park, CA 94025

applying symmetric perfect-electric boundary condition. Power splitting with a designated ratio could also be accomplished on the same waveguide. For instance, the right plot in Fig. 2 shows a 1:2 ratio power splitter design, with the output channel upwards taking one third of the input power from the left input channel. The central adapter controls the power split ratio and impedance matching via several shunt stubs made of the same SOI.

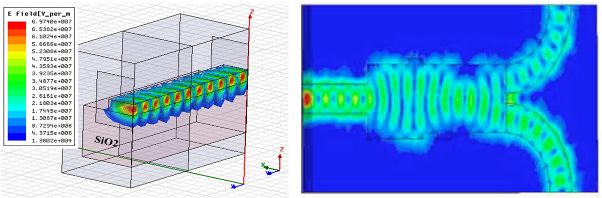

Figure 2: Left, fundamental mode in a 220 nm thick SOI waveguide; Right, 1:2 ratio power splitter based on this waveguide (courtesy of Chen and Webb [5]).

Laser to SOI Waveguide Coupler

Due to the small thickness of the SOI waveguide, mode profile mismatch exists in direct end-coupling with a round-shape laser spot, and results in poor coupling efficiency. The vertical coupling scheme is applied instead. As Fig. 3 shows, the coupler design includes a non-uniform grating structure made on the same SOS wafer. Collective scattering of the gratings directs the incident power from the top into the SOS waveguide connected to the end of the grating region. In Fig. 3, a Gaussian beam of 9 um waist diameter (single-mode fiber output or free-space foci) illuminates the grating along a direction 10° oblique from the vertical normal direction. Image on the left shows the incident field distribution. Shown on the right is the resultant fundamental mode in the SOS waveguide. Evaluation of the integrated Poynting flux over several cross-sectional planes confirms a 70.1% power coupling efficiency from the input laser to the SOS waveguide. Maximum achievable efficiency is about 80% with this coupling scheme [6], due to the profile discrepancy between Gaussian distribution and exponential decay along the longitudinal direction (+*y* in Fig. 3). The grating tooth and slit widths are individually optimized to obtain high efficiency. They range from 220 nm to 410 nm. The slit depth is uniformly 220 nm so that they can be etched by one single exposure. The grating has been successfully fabricated in [6] via a poly-silicon overlay and etching process.

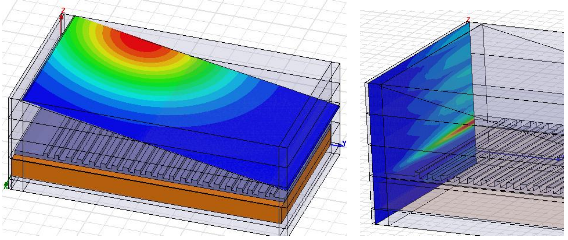

Figure 3: A Gaussian laser beam excites the fundamental SOI waveguide mode via a non-uniform grating coupler.

SOI to Woodpile Waveguide Coupler

The input defect waveguide in the woodpile accelerating cell has an aperture size of 1.537 um by 1.4 um. The cross-section of the silicon slab on the SOI waveguide should in principle have a comparable size as the defect aperture to obtain a good coupling. The width of the silicon slab could be gradually tapered down to 1.537 um before entering the woodpile waveguide. Simulation also proves that tapering the silicon slab height from 220 nm to 1.4 um over a longitudinal distance of 4 um could maintain the fundamental TE mode propagation in the SOI waveguide. In practice, fabrication uncertainty of this tapered SOI may scatter the wave into higher-order modes. A ridge SOI waveguide design could be applied instead to ensure single-mode operation at a large cross-sectional area [7].

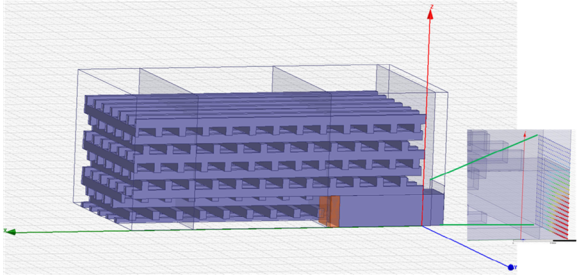

Figure 4: Silicon guide to woodpile defect coupler.

Figure 4 exhibits the proposed design for SOI waveguide to woodpile input waveguide coupling. The silicon square rod extends from the SOI substrate into the woodpile defect, with an insertion depth of 5 um. A ~6 dB reflection exists due to the refractive index mismatch between silicon and air at the end of the silicon rod. A quarter-wavelength impedance transformer, as the orange layer in the figure shows, can be deposited at the interface to suppress this reflection loss. According to calculation, the matching layer should have a refractive index of 1.86 and thickness of 210 nm to provide a reflection null at 1.55 um wavelength. The matching bandwidth is quite narrow, however. A double layer matching section with two materials of different indices could be employed to enhance the matching bandwidth [8].

The coupler has been simulated in HFSS, with 2D waveport excitation to launch SOI fundamental mode along the silicon rod (inset). The open end of the woodpile defect waveguide is terminated by perfect matching boundary to minimize the reflection. A quarter-model with appropriate symmetry boundaries is simulated to decrease the computational size of the problem. The obtained reflection loss is -19.5 dB. Poynting flux integration along the silicon guide and woodpile defect channel shows almost 100% power transmission, confirming a well established forward travelling wave in the woodpile input waveguide.

Coupling to Woodpile Accelerating Mode

The critical coupling section would be the coupling of the photon energy from the woodpile input waveguide into the fundamental accelerating mode along the electron beam channel. Unlike the metallic waveguides applied in RF accelerating cells, both guides in the woodpile are highly overmoded due to their almost-one-wavelength lateral dimensions and not clearly defined boundaries than metallic walls. The aperture size could be shrunk to guarantee single-mode operation; however that may largely increase the difficulty of collimating electron beam along the channel to avoid clipping. The nature of the woodpile defect waveguide being a periodically loaded waveguide in the longitudinal direction further increases the complexity of the problem, because the two-dimensional modal profile launching/coupling scheme is only valid when the waveguide is translationally invariant [9].

Previously, Cowan proposed the T-junction side coupling design similar to the coupler structure constructed by metallic RF waveguides [2]. The coupling was optimized in a reversed way. The fundamental accelerating mode, solved from eigenmode simulations, is launched in the accelerating guide towards the T-junction. The extrusion lengths of several silicon rods at the coupling corner, as can be seen in Fig. 5, were adjusted individually to maximize the power coupled into the coupling guide. Via numerous parametric simulations, it has been found that Rod Y_2 and Y_3 most significantly affect the coupling. An Y_2 and Y_3 extrusion of $0.1a$ and $0.5a$, respectively, yields an optimized coupling efficiency of over 95%, a being the lattice constant. Granted the fields in the coupling guide as the input, reciprocity then guarantees that over 95% total power would be coupled into the right mode in the accelerating guide. However, fields in the coupling guide are hybrids of several woodpile defect modes, which increases the difficulty of coupling that with the SOI waveguide.

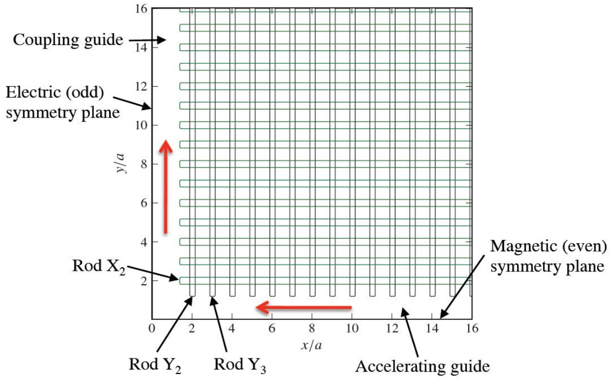

Figure 5: Schematic of the T-junction between woodpile accelerating guide and coupling guide. Several silicon rods are tweaked to optimize the power coupling.

Another challenging way is to design the coupler in the forward direction: excite the woodpile input guide via the silicon guide as shown in the last session, take that input (also hybrid of modes) and try to get the power maximally coupled into the accelerating mode by tweaking the geometry at the corner. The optimization process could be "biased" by applying two magnetic symmetry boundaries in the accelerating guide to rule out non-TM modes. After the coupled power in the accelerating guide is maximized, the fields can be further scrutinized by the field magnitude distribution or unit-cell phase advance to ensure the correct accelerating mode being excited. The advantage of this design philosophy is that the coupler inherits the same launching condition as from the SOI power line; therefore no further adaption to the silicon guide is required.

CONCLUSION AND FUTURE WORK

Various coupling components in the on-chip woodpile accelerator structure have been proposed and designed. Simulations show high coupling efficiencies from them – 70% from laser source to SOI power transport line and almost 100% from SOI waveguide to woodpile input waveguide. A T-junction side coupler is proposed to couple photons into the woodpile accelerating mode. Designing the T-junction coupler in both forward and backward ways are currently under investigation. Formulations to evaluate the mode overlap with arbitrary input fields in a periodically loaded waveguide shall be established, which is also under study. Fabrication and characterization of SOI waveguide and non-uniform grating coupler will be carried out as the first experimental step towards realization of the accelerator structure.

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REFERENCES

[1] C. McGuinness et al., J. Modern Optics 56, 2142 (2009).
[2] B. Cowan, *PRST-AB*, 11, 011301 (2008).
[3] R. Siemann, *PRST-AB*, 7, 061301 (2004).
[4] Ansoft High Frequency Structure Simulator, v. 12.
[5] H. T. Chen et al., Optics Lett. 31(14), 2145 (2006).
[6] D. Vermeulen et al., Optics Express 18 (17), 18278 (2010).
[7] J. Lousteau et al., J. Lightwave Tech. 22 (8), 1923 (2004).
[8] C. A. Balanis, Advanced Engineering Electromagnetics, Wiley, 1989.
[9] R. J. England et al., 14th Advanced Accelerator Concepts Workshop, AIP Conference Proceedings 1299, 445 (2010).