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# A NEW ACCELERATING MODE IN A SILICON WOODPILE STRUCTURE AND ITS HIGH-EFFICIENCY POWER COUPLER DESIGN*

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*Abstract*

Silicon woodpile photonic crystals provide a base structure that can be used to build a three-dimensional dielectric waveguide system for high-gradient laser-driven acceleration. A new woodpile waveguide design that hosts a phase synchronous, centrally confined accelerating mode with ideal Gaussian transverse profile is proposed. Comparing with previously discovered silicon woodpile accelerating modes, this mode shows advantages in better beam loading and higher achievable acceleration gradient. Several travelling-wave coupler design schemes developed for multi-cell RF cavity accelerators are adapted to the woodpile accelerator coupler design based on this new accelerating mode. A forward-wave-coupled, highly efficient silicon woodpile accelerator is achieved. Simulation shows high efficiency of over 70% of the drive laser power coupled to this fundamental woodpile accelerating mode, with less than 15% backward wave excitation. The estimated acceleration gradient, when the coupler structure is driven at the damage threshold fluence of silicon at its operating 1.506 um wavelength, can reach roughly 185 MV/m.

## INTRODUCTION

Laser driven dielectric photonic bandgap (PBG) accelerating structures have drawn great interest due to the potential ~ GeV/m accelerating gradient and mature high-power, high-efficiency lasers as driving sources [1-3]. 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 [4, 5]. 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.

The woodpile structure is an arrangement of high-index dielectric scatters in a low-index background material (e.g. air), following a "woodpile" formation. The schematic in Fig. 1 Inset shows a woodpile accelerating waveguide design first proposed in [4]. The base lattice consists of rectangular silicon rods stacked layer-by-layer, whose collective scattering of light exhibits a three-dimensional photonic band gap. The structure possesses mirror symmetry about the XZ plane, permitting a symmetric monopole mode for acceleration. This mode is confined to the open and roughly rectangular channel, as marked by the red break line in Fig. 1 Inset, and it propagates in the z direction. The accelerator waveguide channel is $7h$ tall and $3a$-$w$ wide along its two transverse directions, with definition of dimensions $w$, $h$, and $a$ illustrated in the figure. Speed-of-light synchronous TM-like mode is present with this waveguide channel design. An integrated on-chip WPS accelerator is conceptually visualized in Fig. 1. An input laser pulse is split into different branches of silicon-on-insulator (SOI) waveguides, represented by solid black channels in the layout, to power multiple stages of woodpile accelerators (meshed cells in the layout). The SOI waveguides are basically silicon slabs sitting atop lower-refractive-index materials, which confine laser light mostly within the silicon by total internal reflection. Control of the flow of the laser power can be realized via splitters and couplers built upon these SOI waveguides [5]. Electrons traversing through the accelerator channel in the WPS waveguide get a kick at each accelerating cell by the laser field, and accelerate. Each accelerator stage contains a woodpile waveguide loop cavity in order to recycle the laser energy and enhance optical-to-beam efficiency, as the rectangular loops in the layout illustrate.

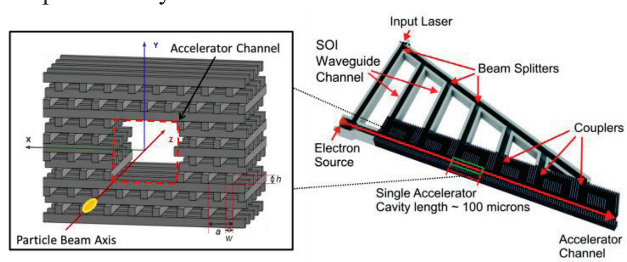


Figure 1: Conceptual schematic of an on-chip woodpile accelerator consisting of multiple accelerator cavities. Inset: Layout of a woodpile accelerator waveguide section supporting speed-of-light accelerating mode. Courtesy of Christopher McGuinness and Benjamin Cowan [4, 6].

## A NEW ACCELERATING MODE

Several Accelerating waveguide designs based on silicon woodpile structure have been proposed before [4, 6]. By adjusting the waveguide aperture size and details at the interface between silicon and the channel wall, modal profile as well as phase/group velocities of the accelerating modes can be fine-tuned [6]. As an example, plotted in Fig. 2, Left is a propagating TM-mode with large longitudinal electric field component for

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acceleration. Parameters of this accelerating mode and a coupler design to transfer laser power to this mode can be found in [6].

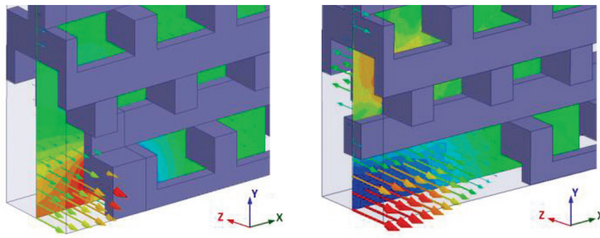


Figure 2: TM-like propagating modes of different woodpile waveguide designs, with their vector electric fields plotted.

Although this old design is a good candidate for laser acceleration and more than 95% power coupling to this mode has been realized, it has a couple of flaws regarding the modal profile in the waveguide. As can be appreciated in its electric field plot, the maxima of the field is located in the silicon at the waveguide wall along +X direction, leaving it prone to laser damage due to the much lower damage threshold of silicon comparing with air. The mode does not resemble a Gaussian distribution over the waveguide opening, with the accelerating field at the core significantly lower than that near the silicon wall. Also, the waveguide has a rather small dimension of $1.175a$ wide and $5h$ tall, therefore more difficulty in beam loading.

In order to overcome these drawbacks, further searching of woodpile waveguide designs are conducted, and an improved accelerating mode has been found. On the right of Fig. 2 its mode profile is illustrated. The new design has an aperture dimension of $4a$-$w$ by $3h$, therefore about 1.9 times as large channel area as the old design for electron transmission (Given the real dimensions of $a$, $w$, and $h$ in [6] for operation at 1.55 um). Its longitudinal field distribution has power concentrated towards the waveguide centre, therefore better matching to electron distribution in a beam spot of presumably Gaussian distribution. This profile is also advantageous in avoiding laser damage to silicon, since energy is mostly confined in the waveguide air core. This mode is a phase synchronous mode. Its dispersion curve intersects with the speed-of-light line at 1.506 um given the dimensions of $a$ = 565 nm, $w$ = 158 nm, and $h$ = 200 nm. Near this wavelength, the mode has a group velocity of $0.109c$ with $c$ being the speed of light constant, which is also slightly higher than the old design so that less wave packet slippage from the injection phase.

## POWER COUPLER DESIGNS

To couple laser power into this new accelerating mode, side coupler design that has been previously investigated [6] is applied again. Basically the design scheme utilizes one silicon rod that is perpendicular to the woodpile accelerating waveguide and extends into the waveguide air core as a guide for the laser power, and applies a travelling-wave launch method that has been developed for RF cavity accelerators to establish the desired propagating mode in the 3-D woodpile PBG waveguide.

### *Back-to-back Symmetric Setup*

A back-to-back symmetric setup is first studied via simulation to design the coupler. The advantage of the back-to-back setup is that it provides an identical end couple-out as the front couple-in, so that no potential mismatch/reflection than if the waveguide end is instead terminated by open space or absorbing boundaries. The disadvantage is that the setup uses symmetric boundary conditions at the front and end of the waveguide; therefore effectively the light is coupled in equally split between forward and backward longitudinal directions.

The layout of Fig. 3(a) illustrates a back-to-back side coupler design for this woodpile accelerating mode. The model is a quarter-symmetric structure, with its front YZ plane and bottom ZX plane assigned perfect magnetic boundaries to simulate TM-like accelerating modes. A pair of silicon rods, having a full width of $3.32w$ and $h$ tall, act as input and output side couplers at the beginning and end of the accelerating waveguide (illustrated in the schematic). Because of the perfect electric boundary condition assigned at the XY planes on the outer boundary of the model, a TE mode polarized in the $z$ direction is excited by a waveport in this coupler rod. This mode is then delivered into the accelerating waveguide, where TE mode to TM mode conversion happens at the coupling corner.

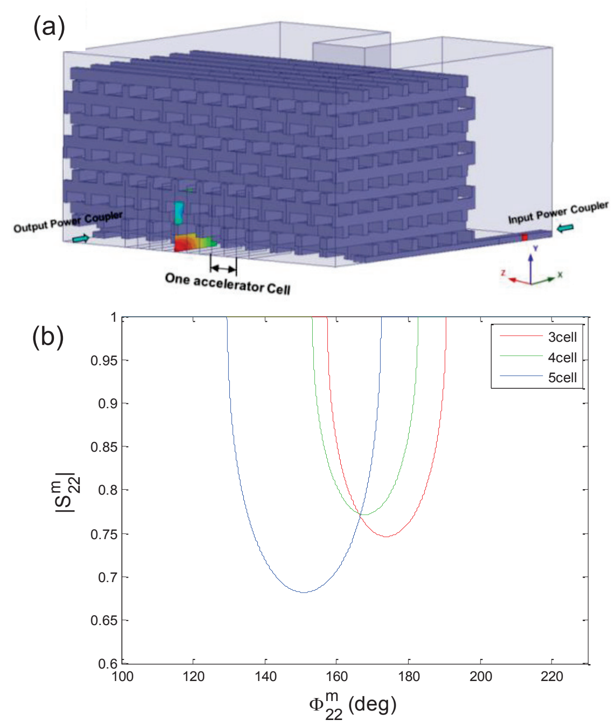


Figure 3: (a) Symmetric TE to TM mode coupler layout for a 9-cell woodpile accelerating waveguide, and (b) its multiple-cell simulation results to determine the required $S_{22}^{m}$ for travelling-wave launch.

As elaborated in [6], the travelling-wave launcher is built by perturbing the TE mode propagation along the power coupler Si rods with an embedded chunk of perfect conductor (red piece, Fig. 3(a)). The multiple-cell simulation result of the $S_{22}^{m}$ magnitude vs. phase is drawn in Fig. 3(b). The curves intersect at a common point, which gives the desired $S_{22}^{m}$ for a traveling-wave mode launcher to have 0.772 magnitude and 166.8° phase. This magnitude and phase is achieved via tuning of the dimensions of the embedded perfect conductor in the silicon coupler guide. A final design after the tuning yields coupling of 76% of the input laser power into the woodpile waveguide, with less than 10% backward-wave-ratio therefore a good travelling wave launch. The launched longitudinal E-field profile, as illustrated in Fig. 3(a) on a transverse cut plane in the accelerating waveguide, closely resembles the desired accelerating mode. Phase synchronous condition is also met, with a nearly uniform phase velocity of 1.0037*c* along the woodpile waveguide.

### *Fully Forward Power Coupler*

To realize a fully forward power coupler, the symmetry electric boundary conditions used on the XY termination planes of the back-to-back model in Fig. 3(a) have to be replaced by open boundaries, or continuation of the woodpile waveguide. In order to avoid laser power going into the backward direction after the input coupler guide, a smaller woodpile waveguide with reduced height is designed as the termination, which exhibits a cut-off to the woodpile accelerating mode and thus prevents light propagation in the undesired direction. Figure 4(a) below shows the schematic of a working forward power coupler design. The schematic is again presenting one quarter of the full structure in its transverse XY plane, to better illustrate its waveguide structures. Very much the same as the back-to-back setup in Fig. 3(a) in the accelerator waveguide section in the middle, this design implements two cut-off waveguide sections at the +/-Z ends of the model to confine the laser power propagation within the accelerator section. The cut-off waveguide has a full dimension of height $h$ along the Y coordinate, and width $8a$-$w$ along the X coordinate. Figure 4(b) and 4(c) give views from the bottom and into the longitudinal direction, respectively, with the opening areas in the structure highlighted to show their boundaries. The light-blue arrows mark the flow of laser power in the structure. The determining dimension for its cut-off condition is found to be its height along Y, and its width dimension could potentially be very large. Therefore, an electron beam of ribbon-like transverse profile would better load charges into this woodpile accelerator. Simulation has proved that the cut-off sections well prevent backward light propagation, directing energy from the input coupler guide into the accelerator section, and coupled out via the output coupler guide. A coupling efficiency of 75.7% is achieved into the new accelerating mode, at its phase-synchronous wavelength of 1.506 um. The backward-wave ratio is about 12% along the accelerating waveguide, suggesting a good travelling-wave excitation. Given this coupling efficiency and taking into consideration the damage threshold fluence of ~ 0.35 J/cm$^2$ for silicon in vacuum at this wavelength, the maximum acceleration gradient that this fully forward coupler can be operated at is estimated to be about 185 MV/m, before it is damaged by laser power and assuming 1 picosecond laser pulse duration.

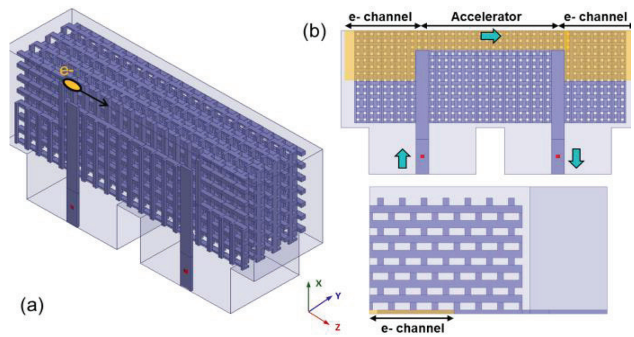


Figure 4: (a) Schematic of a fully forward coupled silicon woodpile accelerator, and (b) its bottom view and side view highlighting its open sections as electron channels and accelerating waveguide.

## CONCLUSION

A new accelerating mode in a silicon woodpile PBG structure has been proposed, with improved transverse profile, acceleration gradient, and group velocity. Previously developed coupler design methods for RF cavity waveguides are applied, and over 70% coupling efficiency of laser power into this accelerating mode has been achieved via silicon guide side couplers. A fully forward coupler is also designed, with cut-off sections terminating the propagation of the accelerating mode outside the accelerator waveguide. In simulations a good energy confinement and a high coupling efficiency of 76% are demonstrated, with an estimated maximum acceleration gradient of 185 MV/m given 1 ps long drive laser pulse duration.

## REFERENCES


[1] E. A. Peralta et al., Nature 503, 91 (2013).

[2] X. Lin, Phys. Rev. ST Accel. Beams 4, 051301 (2001).

[3] J. Breuer and P. Hommelhoff, Phys. Rev. Lett. 111, 134803 (2013).

[4] B. M. Cowan, Phys. Rev. ST Accel. Beams 11, 011301 (2008).

[5] Z. Wu, R. J. England, C. Ng, and S. G. Tantawi, AIP Conf. Proc. 1507, 535 (2012).

[6] Z. Wu et al., Phys. Rev. ST Accel. Beams 17, 081301 (2014).