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Photonic Crystal Laser-Driven Accelerator Structures[1]

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Abstract. We discuss simulated photonic crystal structure designs for laser-driven particle acceleration. We focus on three-dimensional planar structures based on the so-called "woodpile" lattice, demonstrating guiding of a speed-of-light accelerating mode by a defect in the photonic crystal lattice. We introduce a candidate geometry and discuss the properties of the accelerating mode. We also discuss the linear beam dynamics in the structure present a novel method for focusing the beam. In addition we describe ongoing investigations of photonic crystal fiber-based structures.

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INTRODUCTION

Photonic crystals have great potential for use as laser-driven accelerator structures. A photonic crystal is a structure with permittivity periodic in one or more of its dimensions. As described in [1], optical modes in a photonic crystal form bands, just as electronic states do in a crystalline solid. Similarly, a photonic crystal can also exhibit one or more photonic band gaps (PBG's), with frequencies in the gap unable to propagate in the crystal. Confined modes can be obtained by introducing a defect into a photonic crystal lattice. Since frequencies in the bandgap are forbidden to propagate in the crystal, they are confined to the defect. A linear defect thus functions as a waveguide.

High accelerating gradients are possible because photonic crystals can be composed entirely of dielectric materials and benefit from their high breakdown threshold [2]. Photonic crystal waveguides also allow confinement of a speed-of-light mode in vacuum, resulting in high characteristic mode impedance. Another significant benefit of photonic crystal accelerators is that only frequencies within a bandgap are confined. In general, higher order modes, which can be excited by the electron beam, escape through the lattice. This benefit has motivated work on matallic PBG structures at RF frequencies [3, 4]. In addition, an accelerating mode has been found in a PBG fiber structure [5]. We recently completed a study of two-dimensional planar dielectric photonic crystal accelerator structures, demonstrating synchronous waveguide modes and discussing relevant parameters of such modes [6]. Those structures, however, only confine the accelerating field in one transverse dimension. Here we present the design and simulation of a three-

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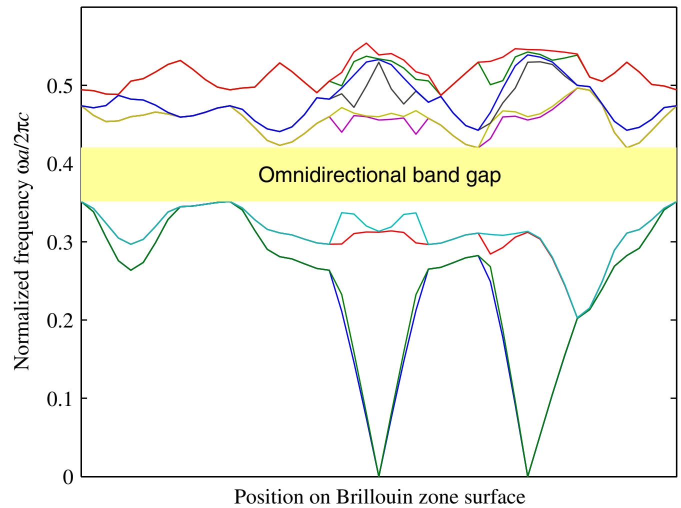

FIGURE 1. The bandstructure of the woodpile lattice.

dimensional planar structure, which overcomes that obstacle and includes a waveguide which fully confines the accelerating mode.

THE WOODPILE LATTICE

The so-called "woodpile" lattice consists of layers of silicon rods in vacuum, with the rods in each layer rotated 90° relative to the layer below and offset half a lattice period from the layer two below, following the geometry described in [7].

We consider laser acceleration using a wavelength of 1.5 µm, in the telecom band where many promising sources exist. At this wavelength silicon has a normalized permittivity of $\varepsilon_r = \varepsilon/\varepsilon_0 = 12.1$ [8]. The horizontal lattice period is then $a = 561$ nm, and the rods are 157 nm wide by 198 nm tall.

The bandstructure of this woodpile lattice is shown in Figure 1. We see from this figure that the lattice exhibits an omnidirectional bandgap—a range of frequencies in which no mode, of any wavevector or polarization, exists.

MODE IN ASYMMETRIC LATTICE

We form a defect waveguide in the lattice by removing all dielectric material in a region which is rectangular in the transverse x and y dimensions, and extends infinitely in the e-beam propagation direction z, as shown in Figure 2.

This waveguide supports an accelerating mode, that is, a mode with speed-of-light phase velocity and nonzero longitudinal field E_z on axis. The accelerating field is shown in the left plot of Figure 3. Examining the fields, we find that there is a vertical deflecting

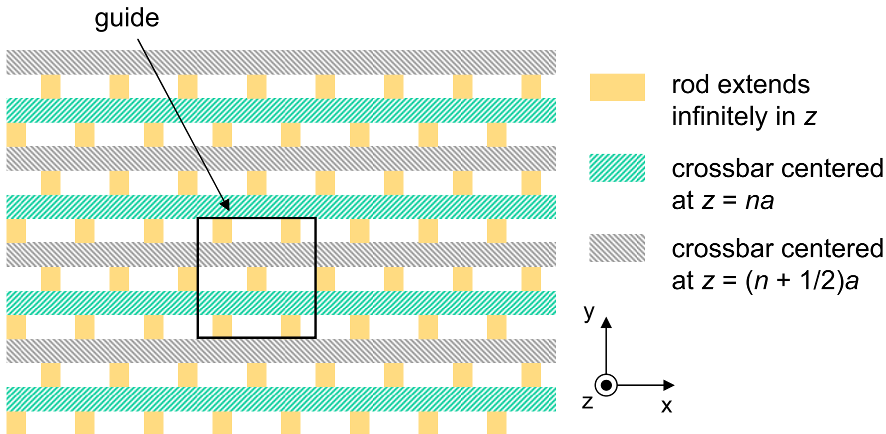

FIGURE 2. The geometry of a waveguide in a vertically asymmetric lattice. The waveguide is formed by removing all dielectric material in the box shown, for all z.

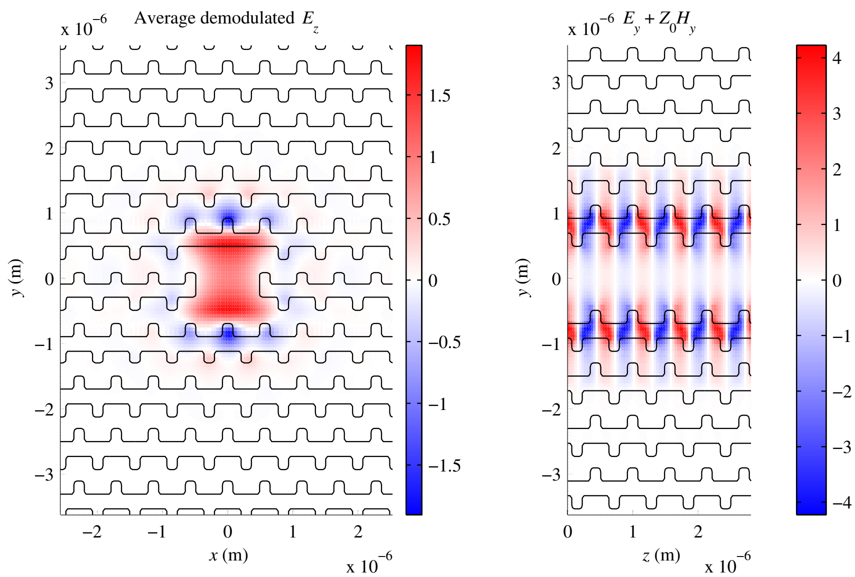

FIGURE 3. Left: The accelerating field seen by a speed-of-light particle, averaged over a lattice period, shown with structure contours for a transverse slice at $z = 0$. Right: The vertical deflecting fields seen by a speed-of-light particle, shown with structure contours for a longitudinal slice at $x = 0$. In both plots the fields are normalized to the accelerating field on axis.

field, shown in the right plot, with magnitude comparable to the accelerating field. This is due to the fact that the structure is not vertically symmetric. In fact, this is an inherent property of the photonic crystal: The lattice geometry itself is not symmetric under reflection across any plane perpendicular to the y axis.

However, the structure is symmetric under the transformation of reflection in y followed by translation of half a period in z. Because of this symmetry, these vertical deflection fields average to zero over a lattice period, so particles will see no net deflection.

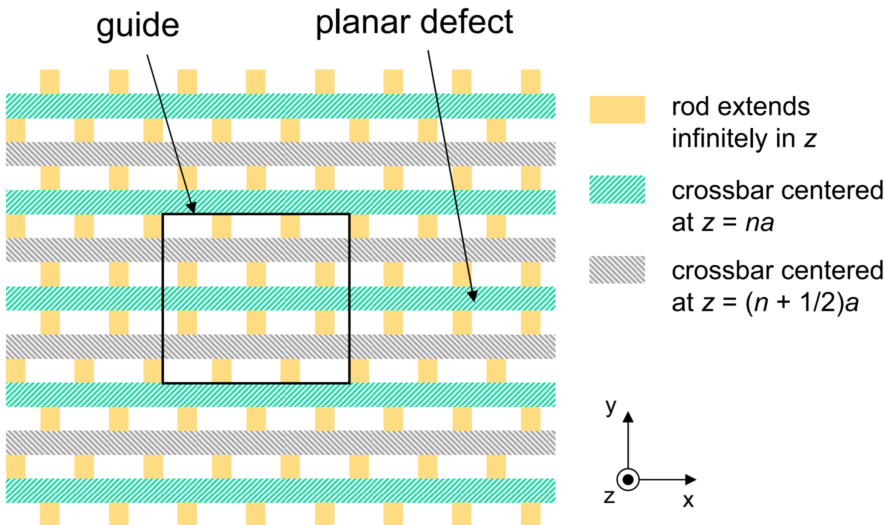

FIGURE 4. The geometry of a vertically symmetric waveguide structure.

Rather, they will see a wiggler field with a period equal to the lattice period of 561 nm.

In examining the beam dynamics of this structure (and others considered here), let us assume an accelerating gradient on axis of $E_{\text{acc}} = 1\,\text{GeV}/\text{m}$. It ought to be pointed out that to the best of our knowledge, the damage threshold of silicon for ultrafast pulses of 1.5 μm radiation is not known. Therefore this field value should be taken only as an example used to examine beam dynamics, not as the breakdown limit of the structure. Investigations of dielectric breakdown have been carried out for other materials and wavelengths [2], and the phenomenon remains an active area of research.

In the case of this asymmetric structure, an accelerating field of 1 GeV/m will result in average synchrotron radiation loss of $\langle dE/dz \rangle = (2.0 \times 10^{-4}\,\text{eV}/\text{m})\gamma^2 = 200\,\text{MeV}/\text{m}$ for 0.5 TeV electrons. Therefore this structure would not be appropriate for use in a high-energy linear collider. To overcome this problem, we must make the structure symmetric in both transverse dimensions to suppress dipole fields.

MODE IN SYMMETRIC STRUCTURE

In order to make the structure vertically symmetric, we invert the upper half of the lattice so it is a vertical reflection of the lower half. The geometry, with a defect waveguide introduced, is shown in Figure 4. This inversion introduces a planar defect where the two halves meet, but the bandgap persists despite the defect.

This waveguide supports an accelerating mode; its fields are shown in Figure 5. In this case the dipole fields are suppressed by the vertical symmetry of the structure. The characteristic impedance of the mode, which describes the relationship between input laser power and accelerating gradient [9], is $Z_c = E_{\text{acc}}^2 \lambda^2 / P = 410\,\Omega$, where P is the laser power. This large impedance value means that for 10 kW of peak power, which is currently attainable using commercially available fiber lasers, the accelerating gradient

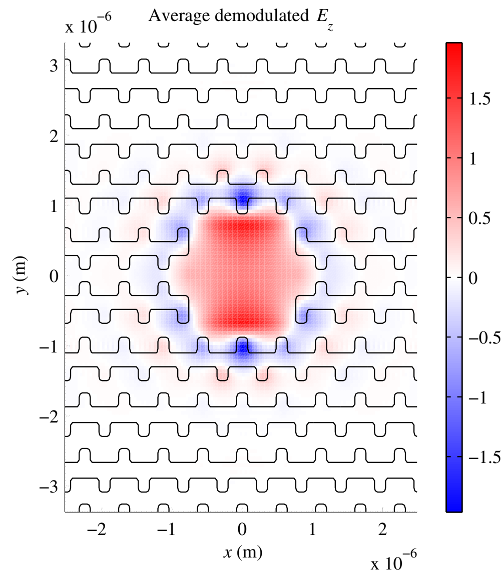

FIGURE 5. The accelerating field seen by a speed-of-light particle, averaged over a lattice period, normalized to the accelerating field on axis, shown with structure contours for a transverse slice at $z = 0$.

on axis would be 1.35 GeV/m.

The damage factor of the mode relates E_{acc} to the maximum electric field anywhere in or on the material. Since laser power is ultimately limited by the breakdown threshold E_{max} of the material, the damage factor is an important measure of the maximum possible accelerating gradient a structure can sustain. For this mode, $f_D = E_{\text{acc}}/|\mathbf{E}|^{\text{material}}_{\text{max}} = 0.24$. Also, the group velocity of the mode is $v_g = 0.245c$. Finally, the physical aperture of the waveguide is $1.53\,\mu\text{m} \times 1.39\,\mu\text{m}$. Because of such a small aperture, a beam with extraordinarily small emittance or a focusing lattice with extremely strong quadrupole strength is required to contain a beam.

OPTICAL FOCUSING

In addition to the small aperture, this structure also presents the problem of strong focusing and nonlinear transverse forces experienced by off-crest particles. Here we consider the linear forces. We define K to be the focusing gradient experienced by a particle 90° ahead of crest. Thus for beam energy E,

$$K = \frac{i}{E} \left. \frac{\partial F_x}{\partial x} \right|_{x=0,y=0},$$

where $\mathbf{F}$ is the force on a speed-of-light particle averaged over a lattice period, and we assume a time dependence of $e^{i\omega t}$ for the fields. For $E_{\text{acc}} = 1\,\text{GeV/m}$, this gives $K = (6.6 \times 10^{14}\,\text{eV/m}^2)/E$, equivalent to a 2.2 MT/m quadrupole magnet. Particles off-

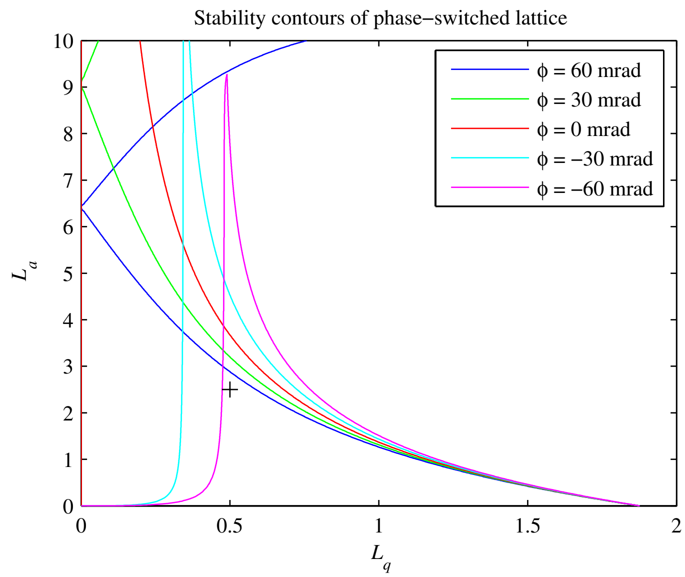

FIGURE 6. Stability contours for a phase-switched lattice. For each optical phase plotted, the lattice is stable in the region beneath the line corresponding to that phase.

crest by a phase ϕ will experience focusing gradients

$$K_x = K \sin\phi, \quad K_y = -K \sin\phi.$$

Thus off-crest particles will be focused strongly in one direction, and defocused strongly in the other. While this presents a problem for beam containment, the presence of such strong focusing fields presents a possible solution not only to the problem of transverse fields but may also overcome the small aperture of the structure: By running the drive laser $\pm\pi/2$ out of phase with the electron beam, we can attain very strong focusing forces that dwarf the natural focusing forces experienced by slightly off-crest particles. Creating a lattice in this manner, the phase offset of a particle from the crest of the fields leads to a small perturbation to the transverse motion rather than wildly different dynamics.

Consider a F0D0 lattice created by adjusting the optical phase ϕ of the drive laser with respect to the center of the electron bunch as follows: Let $\phi = \pi/2$ for a "quadrupole length" l_q of the accelerator; then $\phi = 0$ for an "acceleration length" l_a; then $\phi = -\pi/2$ for l_q, then $\phi = 0$ again for l_a. The properties of this lattice will depend on these lengths normalized to K, so we let $L_q = \sqrt{K} l_q$ and $L_a = \sqrt{K} l_a$. For a given optical phase, this lattice will be stable in a certain region of (L_q, L_a) parameter space. We plot these regions of stability in Figure 6. The region beneath all the curves is stable for any phase ϕ between $\pm 60\,\text{mrad}$. For instance, one such point, marked in the plot, is $L_q = 0.5, L_a = 2.5$. For $E_{\text{acc}} = 1\,\text{GeV/m}$ and $E = 10\,\text{GeV}$, this corresponds to physical lengths $l_q = 1.9\,\text{mm}$ and $l_a = 9.7\,\text{mm}$.

CONCLUSION AND ONGOING WORK

We have found a confined mode in a three-dimensional planar photonic crystal waveguide. This structure has many qualities desirable for a laser-driven accelerator. The mode has a large characteristic impedance, so it could be powered to gradients in excess of 1 GeV/m using readily available fiber laser sources. The photonic crysal lattice has an omnidirectional bandgap, which will simplify coupler design by severely restricting the number of modes into which the laser field can scatter. The structure is amenable to lithographic fabrication, and in fact much work has been done in fabricating this type of lattice [10]; this remains an active area of research in the optics community. Investigation of both coupler design and fabrication for this structure is now a priority.

We have also demonstrated the possibility of confining a particle beam with a phase-switched lattice using the very strong optical focusing fields available in this structure. However, the complete picture of beam dynamics in this structure, including nonlinear forces, is not yet fully understood. Simulation work on this topic is ongoing, and early indications are that the dynamic aperture is small. Also, the optical damage threshold of silicon is not known, and models proposed for other materials suggest that the breakdown limit will be low due to the small electronic bandgap of silicon. In addition, the large photonic bandgap results in three speed-of-light modes being trapped in the waveguide in addition to the accelerating mode described here. These last two considerations suggest investigating other materials to obtain a higher breakdown threshold and a lower index of refraction, which would result in a narrower photonic bandgap.

In addition to the work on the woodpile structure, work is continuing on the photonic crystal fiber structure described in [5]. Experiments are underway to test this structure at W-band frequencies. Also simulations are in progress to design couplers and compute wakefields for this class of structure.

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