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PHOTONIC CRYSTAL LASER-DRIVEN ACCELERATOR STRUCTURES*

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Abstract

We discuss simulated photonic crystal structure designs for laser-driven particle acceleration, focusing on three-dimensional planar structures based on the so-called "woodpile" lattice. We demonstrate guiding of a speed-of-light accelerating mode by a defect in the photonic crystal lattice and discuss the properties of this mode. We also discuss particle beam dynamics in the structure, presenting a novel method for focusing the beam. In addition we describe some potential coupling methods for the structure.

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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 from propagating 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]. In addition, an accelerating mode has been found in a PBG fiber structure [4]. 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 [5]. Those structures, however, only confine the accelerating field in one transverse dimension. Here we present the design and simulation of a three-dimensional planar structure, which overcomes that obstacle and includes a waveguide which fully confines the accelerating mode.

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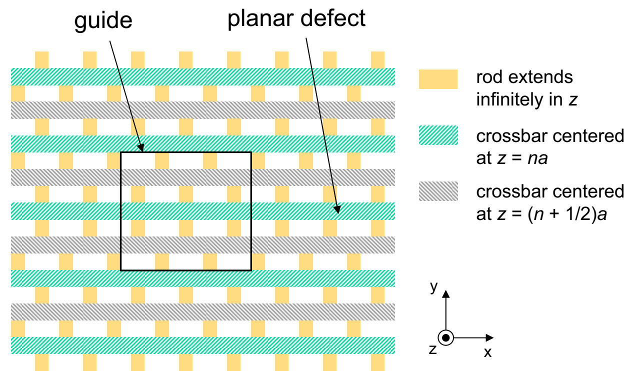

Figure 1: The geometry of a vertically symmetric waveguide structure.

STRUCTURE GEOMETRY

The structure is based on the so-called "woodpile" lattice, which 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 [6].

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 $\epsilon_r = \epsilon/\epsilon_0 = 12.1$ [7]. The horizontal lattice period is then $a = 561\,\mathrm{nm}$, and the rods are 157 nm wide by 198 nm tall. This lattice exhibits an omnidirectional bandgap—a range of frequencies in which no mode, of any wavevector or polarization, exists.

In order to make the structure vertically symmetric to avoid transverse dipole fields, 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 1. 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 2. 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 [8], is $Z_c = E_{\mathrm{acc}}^2 \lambda^2 / P = 410\,\Omega$, 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 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 thresh-

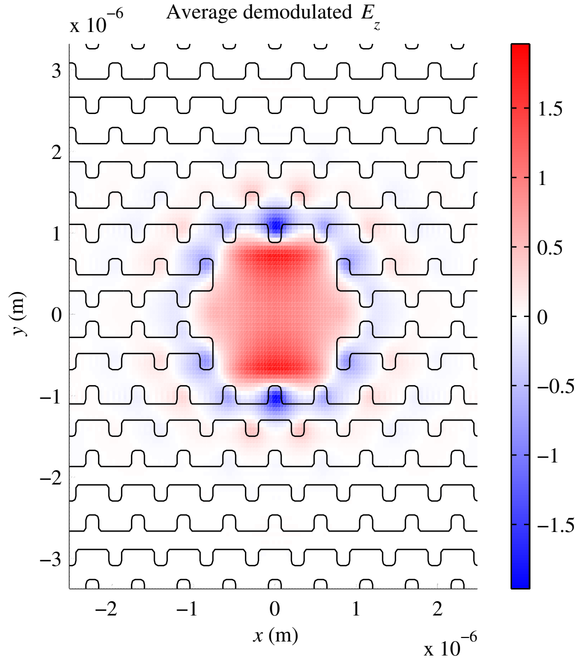

Figure 2: The accelerating field seen by a speed-of-light particle, averaged over a lattice period, normalized to the accelerating field on axis, shown with structure contours for a transverse slice at $z = 0$.

old of the material, the damage factor is an important measure of the maximum possible accelerating gradient a structure can sustain. For this mode, $f_D = E_{\text{acc}}/\left|\mathbf{E}\right|^{\text{material}}_{\text{max}} = 0.24$. 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.

PARTICLE BEAM DYNAMICS

While this structure presents a small aperture, it also raises the possibility of extremely strong particle beam focusing using the optical fields. However, it also presents the problem of strong focusing and nonlinear transverse forces experienced by off-crest particles. We first 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-crest by a phase ϕ will experience focusing gradients

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

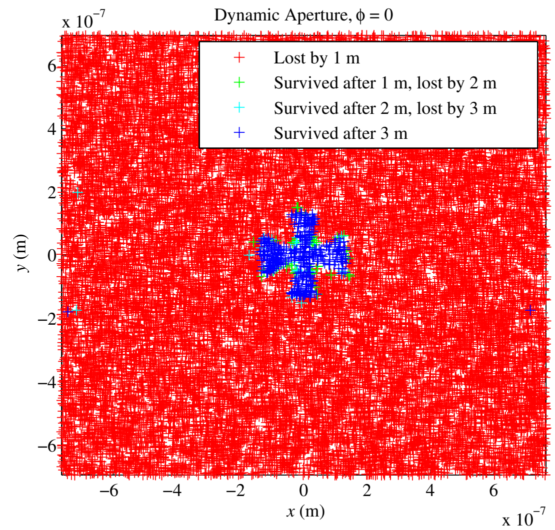

Figure 3: The particles accepted through the dynamic aperture of the system are shown in blue; a fourth-order resonance is visible. The range of the plot is the physical aperture of the structure.

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.

We use this phase-switching technique to construct a F0D0 lattice, which we then model using a particle-tracking code. We simulate the particle proagation exacly, including all phase-space variables and omitting only the negligible effects of synchrotron loss due to betatron motion. The effects of the non-synchronous space harmonics are negligible as well, due the microscopic photonic crystal lattice period, so we use the averaged fields over a single period. We consider an initial particle energy of 10 GeV and an average accelerating field of 1 GeV/m. To compute the dynamic aperture of this system, we track on-crest, mean-energy particles uniformly distributed throughout the physical aperture of the structure and with zero initial transverse momentum. The results of this simulation are shown in Figure 3. The dynamic aperture of this system is small due to the fourth-order nonlinear fields. However, it may be possible to suppress these nonlinearities, and work in this area is ongoing.

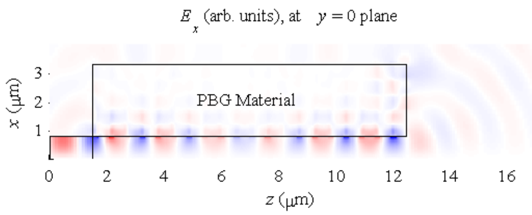

Figure 4: Radiation from an accelerating waveguide into free space. The box in the lower-left corner indicates a metallic input guide used for the simulation.

COUPLING TECHNIQUES

A significant advantage of planar structures which are amenable to lithography is that a coupler from a laser source to the accelerating waveguide can be integrated with the rest of the structure as part of the same manufacturing process. While investigation of such couplers is currently underway, several possibilities have arisen. It should be noted that for the time being, our goal is not to design a near-perfect coupler as would be required for efficient collider operation [9]. Rather, we aim to produce a coupler that has sufficient efficiency for use in a proof-of-principle experiment, given that the input fields are limited by the damage threshold of the material.

The first possibility is simply to attempt to couple directly into the accelerating waveguide from a free-space laser mode. To investigate this, we used FDTD to simulate the reverse problem of radiation from the guide. The result of the simulation is shown in Figure 4. We find that only 7% of the power is reflected at the exit of the guide, indicating that the guide is well-matched to free space.

Another possible coupler involves using two identical accelerating waveguides placed parallel to one another and offset by several wavelengths. In such a structure the eigenmodes are the odd and even modes, and the accelerating mode in a single guide is very well approximated by the sum or difference of the eigenmodes. The beat length between the odd and even modes therefore determines the length required to couple from one guide into the other. We find that for a separation of 7 lattice periods, or 3.9 µm, the beat length is $L = 1816\lambda$, or 2.7 mm.

CONCLUSION

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 simplifies 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 underway.

We have also demonstrated the possibility of confining a particle beam using the very strong optical focusing fields available in this structure. However, the dynamic aperture of the simulated system is small due to nonlinearities. 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 to the work on the woodpile structure, work is continuing on photonic crystal fiber structures such as the one described in [4].

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References

[1] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, Princeton, NJ, 1995).

[2] B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, J. Opt. Soc. Am. B **13**, 459 (1996).

[3] D. R. Smith, S. Shultz, N. Kroll, M. Sigalas, K. M. Ho, and C. M. Soukoulis, Appl. Phys. Lett. **65**, 645 (1994).

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

[5] B. M. Cowan, Phys. Rev. ST Accel. Beams **6**, 101301 (2003).

[6] S. Y. Lin, J. G. Fleming, D. L. Hetherington, B. K. Smith, R. Biswas, K. M. Ho, M. M. Sigalas, W. Zubrzycki, S. R. Kurtz, and J. Bur, Nature **394**, 251 (1998).

[7] D. F. Edwards, in *Handbook of Optical Constants*, edited by E. D. Palik (Academic Press, 1985), vol. 1, p. 547.

[8] J. R. Pierce, *Traveling-wave Tubes* (Van Nostrand, New York, 1950).

[9] Y. C. N. Na, R. H. Siemann, and R. L. Byer, Phys. Rev. ST Accel. Beams **8**, 031301 (2005).

[10] S. Noda, K. Tomoda, H. Yamamoto, and A. Chutinan, Science **289**, 604 (2000).