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Three-Dimensional Photonic Crystal Laser-Driven Accelerator Structures[1]

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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 describe guiding of a speed-of-light accelerating mode by a defect in the photonic crystal lattice and discuss the properties of this mode, including particle beam dynamics and potential coupling methods for the structure. We also discuss possible materials and power sources for this structure and their effects on performance parameters, as well as possible manufacturing techniques and the required tolerances. In addition we describe the computational technique and possible improvements in numerical modeling that would aid development of photonic crystal structures.

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INTRODUCTION

Photonic crystals [1] have great potential for use in laser-driven accelerator structures. Because they can be made entirely of dielectric material, they can take advantage of the high breakdown threshold of dielectrics at optical frequencies [2] to achieve high gradient. Photonic bandgap (PBG) waveguides also allow confinement of a speed-of-light mode in vacuum, resulting in high characteristic mode impedance and thus high efficiency. Three-dimensional photonic crystals—those with complete bandgaps—in particular allow the creation of the compact couplers which are necessary due to the group velocity mismatch between the accelerating mode and the particle beam. Another significant benefit of PBG 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, a benefit has motivated work on metallic PBG accelerators at RF frequencies [3, 4]. In addition, strong particle beam focusing is available from the optical fields in these structures. Finally, planar structures of the kind described here are amenable to lithographic fabrication.

An accelerating mode in a three-dimensional photonic crystal structure has previously been demonstrated, and its basic properties described [5]. Here, we briefly review the geometry of the structure, and concentrate instead on describing some of the unresolved issues this structure raises for photonic bandgap acceleration and structure-based optical

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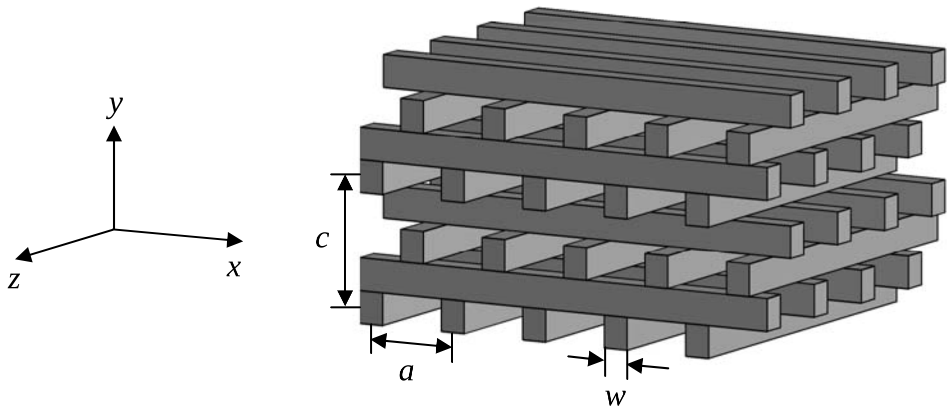

FIGURE 1. A diagram of 8 layers (2 vertical periods) of the woodpile lattice. Here a is the lattice period, $c/a = \sqrt{2}$, and $w = 0.28a$.

acceleration in general. In the following sections, we describe the performance parameters of the structure, including gradient, efficiency, and emittance requirements, and how they might be improved. We also discuss potential materials, sources, computing techniques, and fabrication considerations as they relate to this type of structure.

STRUCTURE GEOMETRY AND ACCELERATING MODE

The structure described here is based on the so-called "woodpile" lattice, which consists of layers of dielectric 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, as shown in Figure 1. For our simulations, we take the relative permittivity of the material to be $\varepsilon_r = \varepsilon/\varepsilon_0 = 12.1$, which is the value for silicon for a wavelength of 1550 nm, in the telecom band where many promising sources exist [6]. (As discussed below, this material and wavelength might not ultimately be optimal for an optical accelerator.) With that permittivity, the woodpile lattice has a complete photonic bandgap—a range of frequencies in which no mode, of any wavevector or polarization, exists [7].

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 on the left in Figure 2. Note that we have inverted the upper half of the lattice so it is a vertical reflection of the lower half, in order to suppress vertical dipole fields.

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 on the right in Figure 2. For this mode, the horizontal lattice period is $a = 0.37\lambda = 580$ nm, and the rods are 162 nm wide by 205 nm tall.

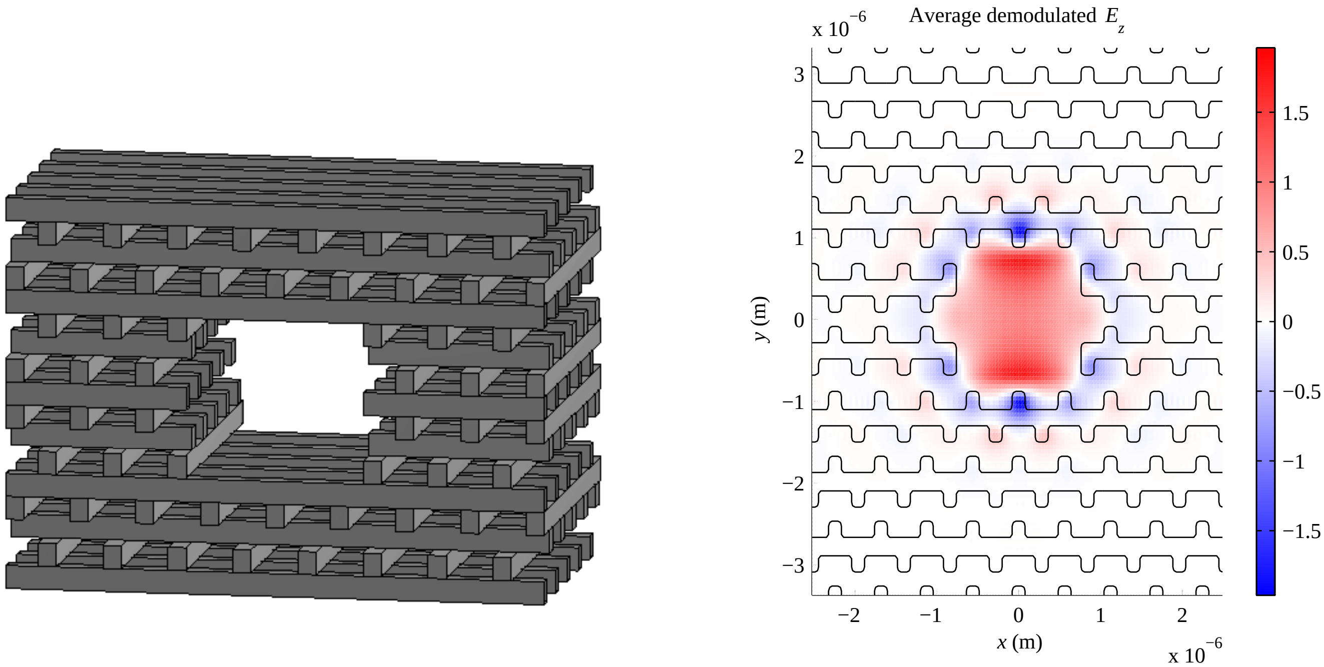

FIGURE 2. Left: The waveguide structure. Right: The accelerating field seen by a speed-of-light particle, averaged over a lattice period, normalized to the accelerating field on axis, shown with structure contours for one transverse slice.

PERFORMANCE PARAMETERS

Accelerating gradient

To describe the possible accelerating gradient of this structure, we define the *damage impedance* by

$$Z_d = \frac{E_{\text{acc}}^2}{2u_{\text{max}}c},$$

where E_{acc} is the accelerating gradient on axis and u_{max} is the maximum electromagnetic energy density anywhere in the material. We choose to relate the accelerating gradient to energy density to reflect the likely importance of multiphoton ionization (MPI) in the damage process [8]. For the woodpile structure, the damage impedance is $6.84\,\Omega$. Preliminary damage threshold measurements of silicon have shown a maximum sustainable energy density of $13.3\,\text{J}/\text{cm}^3$ at $\lambda = 1550\,\text{nm}$ and 1 ps FWHM pulse width [9], resulting in an unloaded accelerating gradient of 240 MV/m. Further measurements have suggested that higher gradients could be achieved at longer wavelengths and shorter pulse widths, but that GeV/m acceleration is unlikely in silicon for near-infrared pulses.

Efficiency

The relevant parameters for structure efficiency are the characteristic impedance, which relates the unloaded gradient to the input laser power P and is given by

$$Z_c = \frac{E_{\text{acc}}^2 \lambda^2}{P} = 410\,\Omega$$

for this structure, and the Čerenkov impedance, which we estimate to be $261\,\Omega$ [10]. Following [10], we find that for these parameters the optimum single-optical-bunch charge is 3.25 fC, with corresponding optical-to-beam efficiency of 12%.

Recently is was shown that efficiency can be improved significantly by embedding an accelerator segment in an optical cavity [11]. Following the treatment given in [11], we find for the woodpile structure that the single-optical-bunch efficiency can exceed 35%, while for a train of 100 optical bunches, the efficiency exceeds 75%.

Coupling efficiency

Efficient coupling is essential to the operation of an accelerator of this type. It is certainly necessary to achieve high optical-to-beam efficiency; indeed, the efficiency computation above assumed only 5% round-trip cavity loss. Efficient coupling is also necessary to achieve high gradient, since a laser pulse will have to be coupled into the accelerating waveguide quite frequently in order to compensate for the group velocity slippage between the pulse and a speed-of-light particle beam. The group velocity of the accelerating mode in the woodpile structure is $0.245c$, so the slippage of a laser pulse in a 1 mm accelerator segment amounts to 10 ps. Therefore a coupler must not only be efficient, but compact as well.

Several coupling techniques have been simulated so far and are described in [5]. For the purpose of a proof-of-principle experiment, coupling via pellicle from a free space mode is sufficient. More than 90% of the power in the accelerating mode couples to free space, no matter where within a period the waveguide is terminated. While a coupler that is both efficient and compact has not yet been demonstrated, such couplers have been simulated for other types of photonic crystal waveguides [12], and efforts in this area are underway.

Emittance requirement

It has been demonstrated that by using the optical fields to focus the particle beam, gradients in the MT/m range are possible [5]. Indeed, a significant length of accelerator must be devoted to focusing in order to overcome the transverse forces on off-crest particles due to the rotationally asymmetric nature of the structure. While the particle motion was found to be stable under linear forces, a fourth-order nonlinear resonance caused the dynamic aperture to be quite small. From the results presented in [5], we can compute the emittance of the particles in the center of the distribution, and from this obtain a required normalized emittance of 3.6×10^{-10} m in each transverse direction. It might be possible to improve the dynamic aperture significantly by adjusting the geometry to suppress the quadrupole fields in the accelerating mode.

ISSUES TO ADDRESS

Material and source considerations

Two major unresolved issues for laser-driven acceleration in photonic crystals are the choice of material and the wavelength of the source. A critical property of a candidate material is its optical damage threshold. Since MPI appears to be a key part of the breakdown process [8], materials with wide electronic bandgaps are desirable. However, this involves a trade-off: A lattice with a complete photonic bandgap generally requires a refractive index contrast $\gtrsim 2$ [7]. But high-index materials tend to have narrow electronic bandgaps, leading to low damage thresholds.

Silicon is once candidate material because it is transparent in the infrared, easy to manufacture, radiation hard [13], and has a high refractive index. However, its electronic bandgap is only 1.1 eV, which may account for the limited sustainable gradient described above. Other materials may strike a better balance between refractive index and electronic bandgap. Possible candidates are rutile (birefringent; $n_o = 2.45$, $n_e = 2.71$, bandgap $\Delta = 3.3$ eV), diamond ($n = 2.4$, $\Delta = 5.5$ eV), and silicon carbide ($n = 2.6$, $\Delta = 3.0$ eV).

Structures such as the one presented here are not limited by laser power availability. Even if a material were found that could sustain 1 GeV/m acceleration gradient, the large characteristic impedance means that at 1550 nm the peak power required would only be $P = E_{\mathrm{acc}}^2 \lambda^2 / Z_c = 5.9$ kW. Such powers are readily available from commercial fiber lasers, so development of sufficiently powerful sources for these structures is not an issue the advanced accelerator community needs to address. However, the role of MPI in optical breakdown also has implications for the choice of source wavelength, as longer wavelengths would tend to suppress this process. A comprehensive study of optical damage thresholds for a wide variety of dielectric materials as a function of both wavelength and pulse duration would serve to inform the design of optical accelerating structures in general. Also, development of efficient parametric generation of doubled wavelengths could be quite beneficial.

Computational issues

The mode computations were done using the MIT Photonic-Bands code, a frequency domain iterative eigensolver [14]. Finding modes of photonic crystal waveguides in the frequency domain is extraordinarily computationally intensive, for two reasons. First, the size of the computational domain is several wavelengths in each transverse dimension. Second, the desired mode is a high-order mode, and targeting it using a spectral transformation results in slow convergence due to the lack of an adequate preconditioner. Therefore we are forced to find all the lower-order eigenstates in addition to the desired mode.

If n is the number of photonic crystal lattice periods in each transverse dimension of the computational domain, then the size of the computational domain is $O(n^2)$. Also, the mode number of the accelerating mode is $O(n^2)$. In addition, at each iteration of the eigensolver, the fields being computed must be orthogonalized against all the lower-order modes. This can dominate the computation time for large numbers of modes, adding another factor of order n^2. Thus the required memory is $O(n^4)$ and the computational time $O(n^6)$. This quickly becomes prohibitive when more lattice periods are required, for instance when computing the modes of a structure with a lower refractive index material and thus poorer confinement. Finding just one accelerating mode for the structure described above requires $\sim 10^6$ CPU seconds on a 2.4 GHz Xeon processor with 16 grid points per lattice period.

A computational technique with more favorable scaling laws would be highly beneficial to the further development of photonic crystal structures. The finite-difference time-domain (FDTD) method [15] is one potential technique. In addition to the more favorable scaling, FDTD allows the implementation of absorbing boundaries, so modeling of radiative loss is possible. Investigation of mode computation using FDTD is underway.

Fabrication considerations

One benefit of planar structures such as the woodpile is that they are amenable to lithographic fabrication using the same tools and techniques as in integrated circuit manufacturing, enabling cost-effective mass production. In fact woodpile lattices of several vertical periods (4–8 layers) have been successfully fabricated for near-infrared wavelengths [16, 17]. While the fabrication processes for each layer is relatively simple, the layer-to-layer alignment is challenging. A tolerance study was performed in which the accelerating mode was computed in structures with each layer randomly misaligned in both horizontal directions with an RMS offset of 0.05 lattice periods, or 29 nm. We found that this resulted in an RMS wavenumber error of approximately 1.4%. That corresponds to a phase slippage of π over 35 wavelengths, or 55 µm. Thus this level of misalignment error is tolerable only if the acceleration length in each segment is shorter than that. Note that in that distance, a laser pulse envelope will slip relative to a speed-of-light particle beam by 550 fs, so the constraints due to misalignment and group velocity slippage are of the same order. Reliable, economical processes for reaching alignment precision well below 25 nm may be possible in state-of-the-art facilities used in the integrated circuit industry, but such tools are not yet readily available for research.

CONCLUSION

Three-dimensional photonic crystal structures hold great promise for laser-driven acceleration. An accelerating mode has been found in a 3D PBG waveguide. It can sustain roughly 240 MeV/m accelerating gradient, but other materials, longer wavelengths and/or shorter pulses are required to achieve GeV/m gradients. The high characteristic impedance means that sufficiently powerful laser sources are readily available at 1550 nm. The optical fields can provide extraordinarily strong focusing gradients, but adjustments to the structure or the focusing technique are necessary to relax the emittance requirement. Finally, technology for reliable, economical fabrication at near-infrared wavelengths likely exists, having been driven by the integrated circuit industry. The ability to fabricate these structures as such technology becomes readily available is an exciting prospect.

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