COMPACT COUPLERS FOR PHOTONIC CRYSTAL LASER-DRIVEN ACCELERATOR STRUCTURES

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Abstract

Photonic crystal waveguides are promising candidates for laser-driven accelerator structures because of their ability to confine a speed-of-light mode in an all-dielectric structure. Because of the difference between the group velocity of the waveguide mode and the particle bunch velocity, fields must be coupled into the accelerating waveguide at frequent intervals. Therefore efficient, compact couplers are critical to overall accelerator efficiency. We present designs and simulations of high-efficiency coupling to the accelerating mode in a three-dimensional photonic crystal waveguide from a waveguide adjoining it at 90°. We discuss details of the computation and the resulting transmission. We include some background on the accelerator structure and photonic crystal-based optical acceleration in general.

INTRODUCTION

Dielectric photonic crystal waveguides have great potential as laser-driven accelerator structures since they can enable high-gradient, efficient acceleration while at the same time taking advantage of the broad understanding of conventional RF accelerator concepts. A photonic crystal is a structure whose permittivity is spatially periodic, with periodicity on the length scale of an optical wavelength [1]. Like electronic modes in crystalline solids, electromagnetic modes in photonic crystals form bands. Certain structures exhibit band gaps, ranges of frequencies in which no mode exists. For frequencies in a band gap, propagation of electromagnetic radiation is prohibited, so a photonic crystal can serve to confine a mode within a waveguide. Unlike index-guiding optical fibers, whose evanescent fields have sub-luminal phase velocity, photonic band gap (PBG) waveguides can confine a speed-of-light mode.

Photonic crystal waveguides have been investigated for some time for metallic RF accelerator structures because of their potential for eliminating a major source of beam break-up instability [2, 3]. In the optical regime, a synchronous mode has been shown to exist in a photonic crystal fiber [4]. Several years ago a study was conducted of two-dimensional planar structures [5]. More recently, a three-dimensional structure design was proposed which incorporates several key aspects of accelerator operation, including high gradient, high efficiency, and stable transverse beam dynamics [6].

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One critical element of a photonic crystal-based accelerator that must be developed is the power coupler. Since the group velocity of the accelerating mode is only a fraction of the speed of light, and short laser pulses must be used to achieve high gradient, coupling of a new pulse into the waveguide must occur frequently. It has been shown that coupling between photonic crystal waveguides on the scale of an optical wavelength is possible [7]. A similar coupler to the accelerating waveguide from an adjoining guide in a photonic crystal must be designed. Such a coupler must be compact, in that it achieves the power coupling in a distance much less than the acceleration distance determined by group velocity slippage. It is this problem of power coupling that we address here.

THE WOODPILE STRUCTURE

We perform our studies of coupling to a photonic crystal accelerating waveguide using the structure described in [6]. This structure, based on the so-called "woodpile" photonic crystal lattice, has the important property of an omnidirectional, or complete, bandgap—the bandgap consists of a fixed frequency interval, independent of direction or polarization, and propagation through the lattice is prohibited for any fields with frequency in that interval [8]. Therefore, in any structure there are a limited number of modes into which fields can scatter. This allows us to tailor devices so that fields propagate into the desired modes, resulting in high-efficiency coupling. This structure is also especially attractive because it was designed to be amenable to lithographic fabrication, in order to take advantage of the extraordinary advances in microfabrication technology driven by the integrated circuit industry over the last several decades.

The 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. The current design of the structure is for an operating wavelength of $\lambda = 1550$ nm, in the telecommunications band where many promising sources exist. We form a waveguide by removing all dielectric material in a region nearly rectangular in the transverse directions and extending infinitely in the particle beam propagation direction. A schematic of this structure is shown in Fig. 1. The horizontal lattice constant of the structure is $a = 565$ nm, and the rods are 158 nm wide by 200 nm tall.

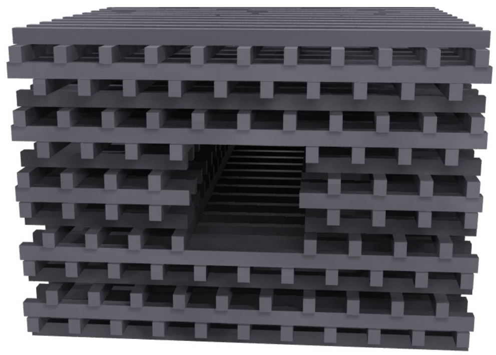

Figure 1: A schematic of a silicon "woodpile"-based structure.

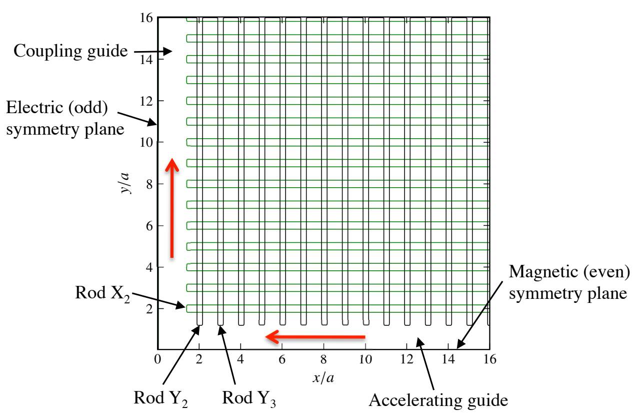

Figure 2: The geometry of the symmetric coupling simulation. The crossbars of the central layer are shown in black; the rods one layer above and below are shown in green. The red arrows indicate the direction of power flow in the simulation.

DESIGN OF COMPACT COUPLERS

To address this design, we began with a problem reduced by symmetry; a schematic of the geometry is shown in Fig. 2. The accelerating waveguide extends along the x axis; the coupling guide adjoins it at 90° and is parallel to the y axis. We imposed the symmetry conditions of an even (magnetic) symmetry across the xz plane through the center of the accelerating waveguide, and an odd (electric) symmetry across the yz plane through the center of the coupling guide. This preserves the on-axis longitudinal field in the accelerating guide, but causes the field in the coupling guide to be primarily transverse. The transverse field in the coupling guide places peak power on axis, to ease coupling between that guide and a fiber or free space mode. In both waveguides, the field on axis is polarized in the x direction. We also imposed even vertical symmetry.

In addition, time-reversal symmetry allows us to compute and optimize this efficiency with simulations of radiation propagating in the opposite direction: from the accelerating mode into the coupling mode. Having computed the analytical form of the accelerating mode, we can find how much power from this mode is coupled into the adjoining waveguide. An advantage of this method is that it guarantees that the coupling efficiency calculated pertains only to the mode of interest – the accelerating mode – rather than to other modes excited at the coupling region. This simulation thus corresponds to incident power coming from both the forward and backward directions in the accelerating guide, and coupling into adjoining waveguides in both the $+y$ and $-y$ directions.

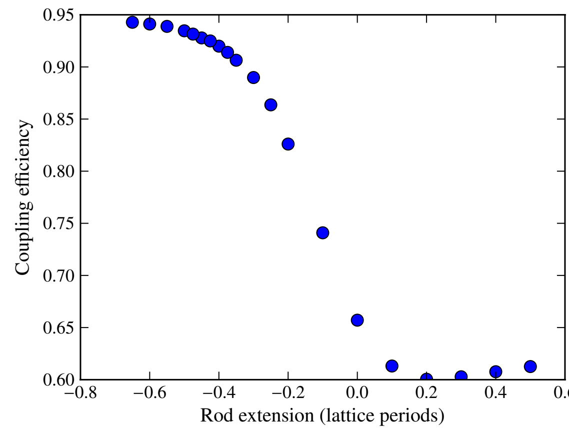

Figure 3: Coupling efficiency vs. extension of rod Y_3.

We studied the coupling efficiency in these systems by running high-performance finite difference time domain simulations with the VORPAL code [9]. We excited the accelerating mode using a narrow-band ramp modulating the accelerating frequency, and ran the simulation until it reached steady state. We determined the efficiency of the coupling by integrating the power flow through the coupling waveguide, and compared it to the incident power measured by simulating a straight accelerating waveguide without a coupler. To avoid the problem of multiple reflections at the ends of the waveguides, we used absorbing layers overlapping the outer 4 periods of the structure.

The coupling efficiency for our initial geometry, shown in Fig. 2, was 65%. To improve this, we adjusted the geometry by extending or retracting individual rods. Since the rod length is set by an exposure mask in fabrication, these adjustments are amenable to the existing lithography process. We performed parameter scans of various rod adjustments. We denote the rods by their location and central direction; for instance, the rod which extends in the y direction and is centered at $x = 2a$ is denoted Y_2, and other rods are denoted similarly. The first parameter scan we performed was of rod Y_2, but adjusting this rod had only a marginal impact on the efficiency.

By contrast, adjustment of rod Y_3 showed remarkable results, which are shown in Fig. 3. We see an increase in coupling efficiency from ~65% to nearly 95% as the rod is extracted out of the accelerating waveguide. Then, re-

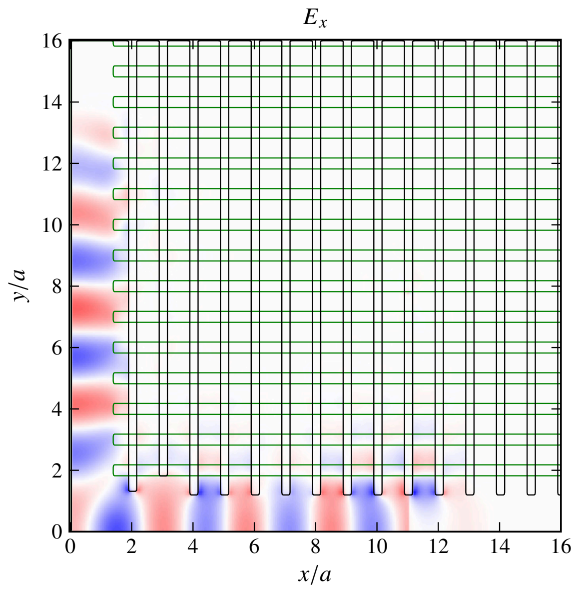

Figure 4: The fields propagating from the accelerating to the coupling guide in the symmetric coupler, with 97% power efficiency. The fields were launched at a surface at $x = 11a$.

visiting the adjustment of rod Y_2, extracting that rod out of the waveguide by $0.1a$ improved the coupling efficiency yet further, to 97%. We show the propagating fields in this case in Fig. 4.

Starting from this symmetric result, we then extended our simulations to the asymmetric case of couplers from the coupling guide to the forward direction only in the accelerating guide. We included both the forward and backward directions in the accelerating guide, breaking the symmetry we had previously imposed. However, we continued to use a time-reversed simulation, launching the accelerating mode from the forward direction in the accelerating guide, and optimizing the power flow to the coupling guide. The initial simulation, using the geometry from the symmetric case, was promising, with coupling efficiency at ~80%. Adjusting rod X_2 to the left of the coupler improved the efficiency to 92%. We then ran the simulation forward in time, launching toward the coupler the fields that were propagating into the coupling guide in the time-reversed simulation. A plot of the fields in this simulation is shown in Fig. 5; the power efficiency for coupling into the forward direction in the accelerating guide was found to be 91.5%.

Thus, we have shown that high-efficiency couplers amenable to lithographic fabrication can be designed, with improvements in coupling efficiency being achieved by adjustments of individual rods.

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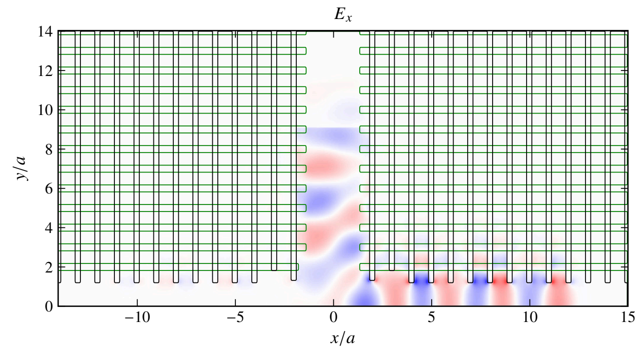

Figure 5: The fields propagating from the coupling guide to the forward direction in the accelerating guide, with 91.5% power efficiency. The fields were launched at a surface at $y = 9a$.

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