OPTICAL WAKEFIELD FROM A PHOTONIC BANDGAP FIBER ACCELERATOR*

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Abstract

Photonic Bandgap (PBG) structures have recently been proposed as optical accelerators for their high coupling impedance and high damage threshold. As a first step in preparing a PBG accelerator, we propose to observe the optical wakefield induced by an electron beam traversing the structure in the absence of a coupled laser pulse. The electrons are focused into the fiber via a permanent magnet quadrupole triplet. The electrons excite fiber modes with speed-of-light (SOL) phase velocities. By observing the wakefield using a spectrometer, the SOL mode frequencies are determined.

INTRODUCTION

An interesting possibility in the pursuit of ever greater accelerating gradients is the use of lasers instead of RF fields to accelerate. Laser design and development is a huge industry as well as research field. In the past decade lasers have reached wall-plug to photon efficiencies of over 50% and peak fields far in excess of what can be sustained in an optical structure. Lasers allow the use of very short pulses closer to the electron pulse length which allows higher peak electric fields and thus higher acceleration gradients. Perhaps more importantly, a switch to optical wavelengths makes interesting the use of dielectric structures to confine fields rather than metallic structures. At optical frequencies dielectrics can sustain more than an order of magnitude greater peak fields than metals.

PBG structures are a quickly growing topic of study in the optics community. They have demonstrated an ability to manipulate light on a microscopic scale, guiding and confining by an interference effect rather than by total internal reflection as in conventional optical fibers and without the use of metallic surfaces typical of RF or microwave devices. Within the telecomm industry, structures with an air core are of interest for their potential low-loss, but these are also now being explored as potential accelerator structures where the air-core can serve as a vacuum channel for an electron beam[1, 2].

The potential use of hollow-core dielectric fibers as particle accelerators bring up many unique challenges from typical telecomm applications. Accelerating modes differ significantly from fundamental core modes in their field profiles, having the greatest field strengths at the inner most surface rather than in the center of the core. As a consequence, the accelerating modes are more easily perturbed by fabrication errors in the fiber than the core modes. Also, whereas telecomm applications are primarily concerned only in the transmission loss of a fiber, the application as an accelerator has stricter demands on the mode. In particular the mode must have a phase velocity within 0.1% of speed-of-light. Unlike RF waveguides which can be diagnosed directly by bead pulls for example, direct examination of fiber fields is much more difficult. It therefore becomes interesting to consider probing candidate structures using the electron beam itself. Once potential SOL accelerating modes are identified, the fiber can later be excited from light generated by an optical parametric amplifer.

Before attempting such an experiment, we simulate the structure using the particle-in-cell code Magic[3]. A short section of fiber is excited by a short electron pulse whose duration is less than the wavelengths of interest. In the simulations to follow, a pulse is emitted off of a conducting boundary and propogates down the fiber. Perfectly matched layer (PML) boundaries at the perimeter of the simulation absorb outgoing radiation. Various monitors within the simulation monitor $E_z(t)$ and the flux generated by the beam. Although the emission from the beam in the simulation is coherent, we can also use the results to calculate the amount of incoherently generated wake from a longer electron pulse in the actual experiment.

RESONANT CHERENKOV WAKEFIELD FROM A BRAGG FIBER

The first fiber examined is an azimuthally symmetric Bragg structure. The fiber consists of a multilayer dielectric with varying index of refraction. The layer thicknesses are chosen to determine the confined wavelength. The innermost layer has a unique thickness to give the confined mode a SOL phase velocity. A full prescription for choosing the layer thicknesses can be found in reference [4]. For the simulation the fiber was designed to have a 1.5 μm accelerating mode. It is worth noting that while fibers with this specific design do not yet exist, Bragg fibers have been fabricated for other purposes, both with a silica-air layering[5] and two types of dielectric[6].

A simulation (figure 1) of a fiber Bragg structure shows the formation of a wake. The inset shows a cross-section of the fiber. On the right of figure 1 is an fft of the on-

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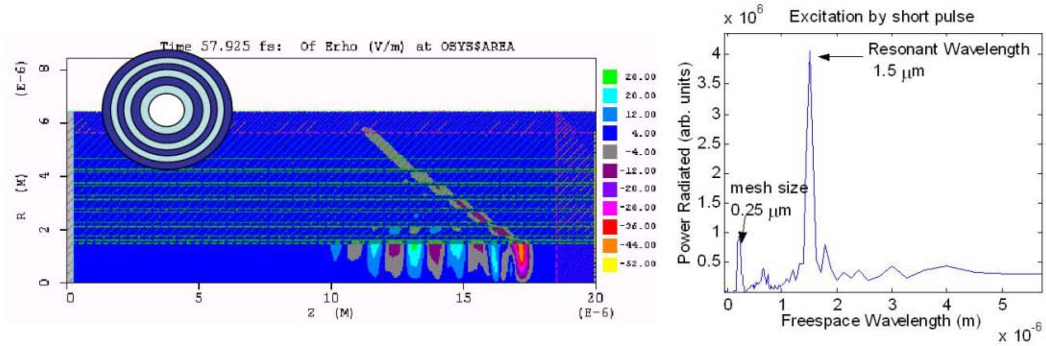

Figure 1: 2D simulation of the wake generated in a Bragg fiber. Left: Snapshot of E_r in the fiber. Note the Cherenkov angle within the bulk dielectric and the wake generated. The inset shows the cross-section of the fiber. Right: Fourier transform of the on-axis E_z field showing the resonance at the expected wavelength of 1.5μm.

axis E_z field near the end of the fiber to give a sense of the resulting spectrum. The resonance is clear in both the simulation snap shot and resulting spectrum. Although the simulation is for a very short electron pulse, we can infer the amount of incoherent excitation from a long pulse. The total energy radiated into the accelerating mode from a 50 pC bunch is 0.1 nJ with an additional 2 nJ of non-resonant Cherenkov radiation leaking out the sides of the fiber.

THE 2-D CASE: THORLABS HC-1550 FIBER[7]

While a custom fiber designed specifically for laser acceleration is being pursued, the appeal of using a commercially available fiber is obvious. The design and development as well as many of the diagnostic measurements are already done. Thorlabs Inc. currently has available a range of air core photonic bandgap fibers that may potentially be suitable as accelerator structures. For instance, the HC-1550-02 fiber designed to support an HE_{11} fundamental mode at 1.55μm has also been found to support a SOL accelerating mode at 1.89μm[8].

The HC-1550 has an inner core of 10.9μm, much larger than the wavelengths of the modes themselves. As a result, the waveguide is both highly overmoded and also less strongly coupled to the electron beam. The induced wakefield is less obvious in snap shots of the simulation (figure 2). However, as with the Bragg fiber, an examination of the E_z field on axis shows excitation of modes in the near IR. For example we see excitation at 1.89μm where previous simulation with the code CUDOS found a SOL mode[8]. The simulation of the HC-1550 fiber remains an on-going effort in preparation for plans to test a real fiber with an electron beam.

THE PMQ TRIPLET

As with conventional RF and microwave structures, most structures for laser acceleration have transverse apertures comparable to the accelerating wavelength. For laser acceleration ($\lambda \approx 1\mu$m) this presents unique challenges for electron focusing and transmission through the structures. Optimal transmission can be achieved when β^* equals half the length of the optical accelerator. The structure length will be a few millimeters, determined by the slip of the laser pulse relative to the electrons due to the lower group velocity. Unfortunately the standard quadrupole triplet installed ahead of the experiment can only achieve spots with $\beta^* = 3cm$ limited by chromatic aberration. To get stronger focusing, a permanent magnet triplet was designed and fabricated to sit in vacuum $2cm$ upstream of a candidate structure.

The PMQ triplet was designed using the Radia [9] magnetostatic simulation code. Each quadrupole has four magnet blocks and four iron pole tips held in an aluminum yolk. The center aperture is 3mm in radius. The magnet blocks are 20 mm high, the iron poles 16 mm. The pole tips are flat to simplify fabrication. The triplet consists of one thinner quadrupole at 7 mm and two thicker quadrupoles, 13 mm each. The thinner quadrupole has a strength of 480 T/m, the larger two are 530 T/m.

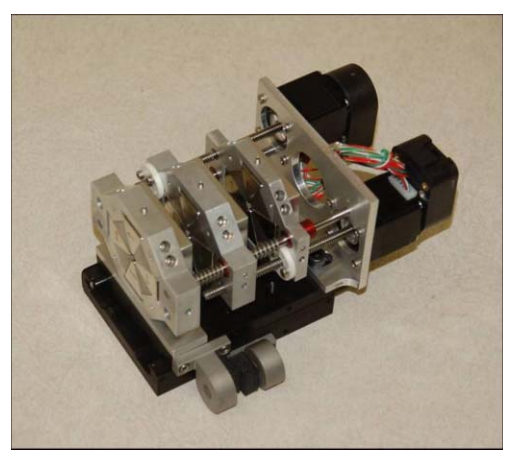

Figure 3: The Permanent Magnet Quadrupole triplet. The first two quads are movable by stepper motor to adjust the final focus, as is the assembly as a whole.

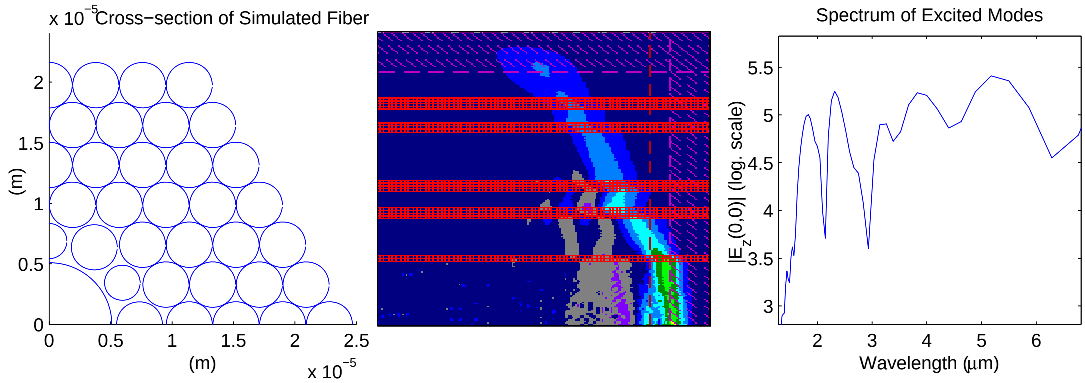

Figure 2: Left: Approximated cross-section of HC-1550 used in simulation. Center: Snap-shot of E_z field produced by beam traversing fiber. Right: Resulting spectrum excited by the electron beam.

The quads sit atop a common mount, with the two upstream quads driven by stepper motors for tuning. Tuning with the quad gaps allows the triplet to accommodate a range of beam energies and also can correct for an initial beam asymmetry or differences in quad strength due to fabrication error. A third motor moves the stage as a whole to locate the focal point. Figure 3 shows a picture of the entire triplet. Further information on the design, fabrication, and measurement of the PMQ triplet can be found in [11]. The triplet was fabricated in house at SLAC.

THE PLANNED EXPERIMENT

The actual experiment will likely employ a fiber coupled spectrometer with a range of 300-1000nm. Thorlabs makes other fibers similar to the HC1550 but with scaled down dimensions which should have accelerating modes within the range of the spectrometer. To simplify coupling to the spectrometer, a long length of fiber will be used with one end illuminated by the electron beam and the other going to a butt coupled fiber optic vacuum feedthrough. This will have the drawback that the electron beam will pass through the glass of the fiber as it expands away from the focus of the PMQ triplet. However, for the relatively short time in which the fiber will be used, degradation of the optical quality of the glass due to radiation damage is expected to be minimal.

In order to determine if the electron beam is indeed coupling directly into the fiber aperture, a pellicle mirror and microscope objective will be placed in vacuum so as to image the front face of the fiber. Optical transition radiation off of the face of the fiber will serve to mark the beam location when mis-steered.

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