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Experiment to Detect Accelerating Modes in a Photonic Bandgap Fiber[1]

R. J. England*, E. R. Colby*, R. Ischebeck†, C. M. McGuinness*, R. Noble*, T. Plettner*, C. M. S. Sears†, R. H. Siemann*, J. E. Spencer* and D. Walz*

*Stanford Linear Accelerator Center, Menlo Park, CA 94025
†Max Planck Institute for Quantum Optics, Garching bei Muenchen, Germany

Abstract. An experimental effort is currently underway at the E-163 test beamline at Stanford Linear Accelerator Center to use a hollow-core photonic bandgap (PBG) fiber as a high-gradient laser-based accelerating structure for electron bunches. For the initial stage of this experiment, a 50pC, 60 MeV electron beam will be coupled into the fiber core and the excited modes will be detected using a spectrograph to resolve their frequency signatures in the wakefield radiation generated by the beam. We will describe the experimental plan and recent simulation studies of candidate fibers.

INTRODUCTION

In traditional microwave structures, the breakdown limit for metallic surfaces limits the accelerating gradient to around 100 MV/m. Consequently, obtaining beam energies that are interesting for high energy physics applications (> 100 GeV) requires beam lines that are multiple kilometers in length. The logistics and costs associated with the construction of such facilities are becoming increasingly cumbersome with the push to achieve beam energies in the TeV range and beyond.

It is therefore critical to develop new technologies for particle acceleration which combine higher gradient (> 200 MV/m) acceleration with reduced cost. One possibility which has been explored in recent years is the use of micron-scale dielectric structures driven by lasers operating in the optical to near infrared regime. The use of a laser as the drive source for the accelerating field offers several benefits, including the high rep-rates (>10 MHz) and strong electric fields (> 0.5 GV/m) which modern lasers can provide, combined with improved commercial availability and cost when compared with microwave sources. The use of dielectric structures circumvents the problem of power loss in metallic cavities at optical frequencies; it also allows for much larger accelerating gradients due to the higher breakdown thresholds (1-5 GV/m) of dielectric materials.

One class of such structures is a hollow-core dielectric fiber. The core serves as both a channel for the accelerated beam and as a guide for a propagating accelerating mode. The simplest configuration is a circular metallic waveguide, with a dielectric lining

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that serves to slow the phase velocity of the TM_{01} mode to the speed of light [1]. However, the requirement of a conductive outer boundary makes this design non-ideal for a laser-driven scenario, since the attenuation length for metallic waveguide at optical wavelengths is on the order of 50 μm. Other configurations overcome this difficulty by using, for example, either a series of dielectric layers of alternating permeability to form a Bragg reflector around the hollow core [2], or by using a periodic array of air-holes to form a photonic bandgap (PBG) lattice which likewise confines the mode within the (larger diameter) central hole [3].

The azimuthal symmetry of the Bragg configuration makes it attractive from the perspective of computational and analytical analysis. However, due to the commercial availability of PBG fibers, and the larger central aperture radius which this geometry allows (approx. 0.7 λ vs. 0.3 λ for the Bragg case), our recent investigations have focused on PBG fibers. The goal of these investigations is to study the use of PBG fibers as potential laser-based accelerating devices through a combination of experimental and computational efforts. In the present paper we present the results of our recent investigations as well as plans for future experiments.

BACKGROUND AND RECENT RESULTS

A photonic bandgap fiber geometry with circular air holes, optimized for use as an accelerating structure, has been proposed by Lin [3], with variations examined by Cowan, et al. [4]. This configuration uses a hexagonal lattice in fused silica ($\varepsilon = 2.13$), with air holes of radius $r = 0.35a$, separated by a center-to-center distance $a = 1.31\lambda$, where λ is the wavelength, and with a larger central hole of radius $R = 0.52a$. These parameter values are configured so as to produce a TM_{01}-like accelerating mode in the center of the lowest bandgap. This mode has a phase velocity equal to the speed of light ($v_\phi = c$), and is fairly well isolated from other nearby modes.

The sustainable accelerating gradient in this structure is a function of the damage threshold of the dielectric, which in turn is strongly dependent upon the laser pulse length. Group velocity slippage of the laser pulse envelope imposes a lower limit on the pulse length $\sigma_t > (1 - v_g/c)L$ where v_g is the group velocity and L is the fiber length. For this structure, $v_g = 0.58$, so for a 1 mm long fiber the minimum laser pulse is about 1ps. The damage threshold for 1 μm light in SiO_2 at this pulse duration is approximately $E_{max} \approx 5$ GV/m. The ratio of the peak electric field inside the dielectric to the on-axis field (referred to as the "damage factor") is $DF = 2.1$. Consequently, the accelerating gradient cannot exceed $E_z = E_{max}/DF \approx 2.5GV/m$.

TABLE 1. Lin Fiber Parameters for Different Core Radii

Parameter	**Case 1**	**Case 2**	**Case 3**
Defect Radius R (μm)	0.678	1.75	2.74
Wavelength λ (μm)	1.01	1.01	1.01
Cherenkov Loss Factor (V/C)	3.92e+22	5.88e+21	2.40e+21
Characteristic Z_c (Ω)	19	0.7	0.15
Loss Factor (V/C)	3.26e+21	1.20e+20	2.57e+19
Damage Factor DF	2.1	8.0	15.6

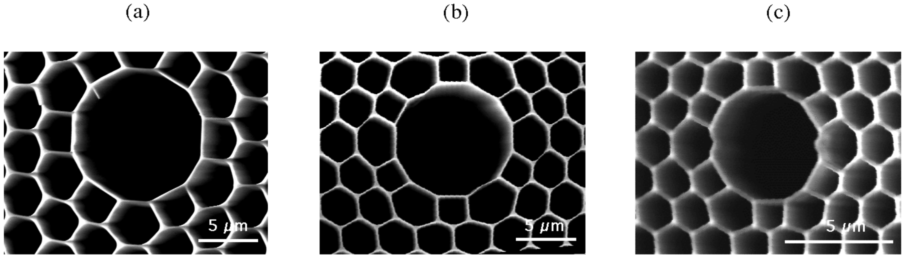

FIGURE 1. Scanning electron micrograph images taken of three different commercial fibers: (a) HC-1550, (b) HC-1060, and (c) HC-633. The numerical suffixes are the telecom frequencies in nm. Inset bars show relative length scales.

Damage factors for the Bragg and dielectric waveguide geometries are also of order $DF = 2$, and hence yield comparable accelerating gradients. However, the central aperture of the PBG geometry is more than a factor of two larger for the same wavelength, making the problem of coupling an electron beam into the fiber core and transmitting significant charge through it somewhat less difficult. However, for a 1 μm drive laser, the resultant core diameter of 1.36 μm still poses a significant challenge from the perspective of beam aperture. As shown in Table 1, the central defect radius may be increased further, but at the expense of significantly increasing the damage factor and reducing the characteristic impedance of the mode.

We have investigated a number of commercially available PBG fibers whose geometries are similar to that of Lin. The fibers studied were manufactured by Crystal-Fibre, Inc. Scanning electron micrograph (SEM) images of the cleaved cross-sections of three fibers are shown in Fig. 1. The fibers in Fig. 1 were designed for telecom use and consequently support bandgap modes that are not desirable from the perspective of particle acceleration. Note also that their lattices more closely resemble a hexagonal honeycomb shape than the matrix of circular holes proposed by Lin in Ref. [3], and display more complicated structural features near the central defect. These geometrical features were carefully duplicated in simulations using the commercial code BandSolve (RSoft Design Group, Ossining, NY), in order to realistically model the fiber modes. The simulation results indicate that all three fibers will support modes with a nonzero longitudinal electric field on-axis; however, the simulated axial electric field strength approaches zero as their dispersion curves are followed toward the speed-of-light (SOL) line.

The most promising SOL accelerating mode was found in the HC-1060 fiber of Fig. 1(b). The simulated geometry and E_z field contour are shown in Fig. 2. Corresponding values for characteristic impedance, damage factor, loss factor, and group velocity for this mode were found to be: $Z_c = 0.005\Omega$, $DF = 166$, $P_{loss} = 0.015$ dB/mm, and $v_g = 0.81c$ respectively. For these parameter values the HC-1060 fiber could sustain a maximum theoretical accelerating gradient of only 30 MV/m. Furthermore, because these fibers are designed for telecom use the bandgap is heavily overmoded. Consequently, the commercial telecom fibers are likely to be unsuitable as off-the-shelf high gradient (GV/m) accelerators, but could prove valuable as surrogate structures for con-

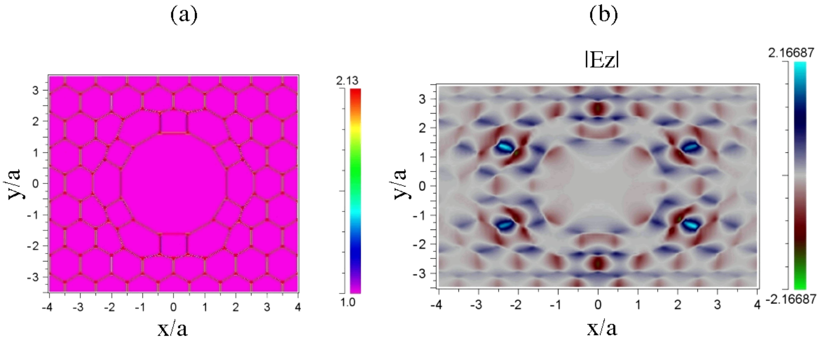

FIGURE 2. Plots of (a) simulated lattice geometry (as dielectric constant contour plot) and (b) contour plot of E_z for the accelerating mode in the HC-1060 fiber.

ducting proof-of-principle experiments and for developing tools and technologies suited to the task of coupling lasers and electron beams into fibers. An experimental test setup at the E-163 test facility at SLAC has recently been constructed to address these issues.

EXPERIMENTAL SETUP

The E-163 beam line at SLAC uses the 50pC, 60 MeV electron beam generated by the Next Linear Collider Test Accelerator (NLCTA) to study various laser-driven structures for advanced accelerator applications. Initial PBG fiber experiments, depicted in Fig. 3(a), will examine the beam-driven excitation of wakefields in several sample fibers, including those shown in Fig. 1. The electron beam will be focused into the central aperture of the fiber using a triplet of permanent magnet quadrupoles (PMQs), which are described in Ref. [5]. After 1 mm of propagation distance the fiber is bent rapidly out of the way (on a 3mm radius) and sent to a spectrograph where the frequency signatures of excited fiber modes can be spectrally resolved. Once a candidate fiber with a suitable accelerating mode is identified, future experiments will use an external laser to excite this mode, as depicted in Fig. 3(b), and thereby accelerate an optically microbunched electron beam. The microbunching scheme, which uses an inverse free-electron laser (IFEL) interaction to impart an energy modulation that is then translated into spatial bunching by a chicane, was recently demonstrated [6].

The apparatus for the first-pass experiment of Fig. 3(a) is depicted in Fig. 4. The PMQ assembly is fitted with movers to adjust the magnet spacing and distance from the fiber, which is mounted on a 4-axis motorized stage assembly that can translate, tip, or tilt the fiber in the plane transverse to the beam axis, with approximately 50 nm resolution. The fiber holder, shown schematically in Fig. 4(b), incorporates a YAG profile monitor and a tantalum knife-edge for measuring the transverse spot size of the e-beam. Four different fibers (currently those of Fig. 1 plus a fourth 800nm telecom fiber) are mounted in the holder, and then moved into or out of the beam path by translating the stages.

The fibers exit the vacuum chamber via a feedthrough flange and then are coupled to

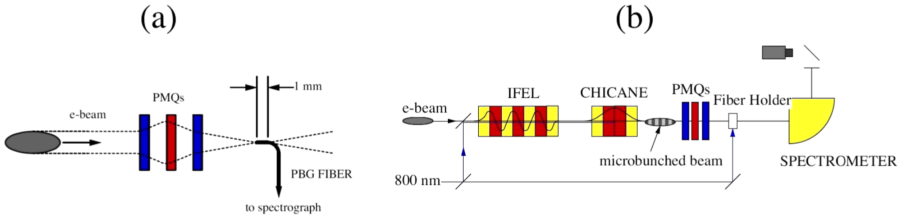

FIGURE 3. Illustrations of experimental setups for (a) initial wakefield measurements of fiber modes and (b) a laser-driven accelerator scenario.

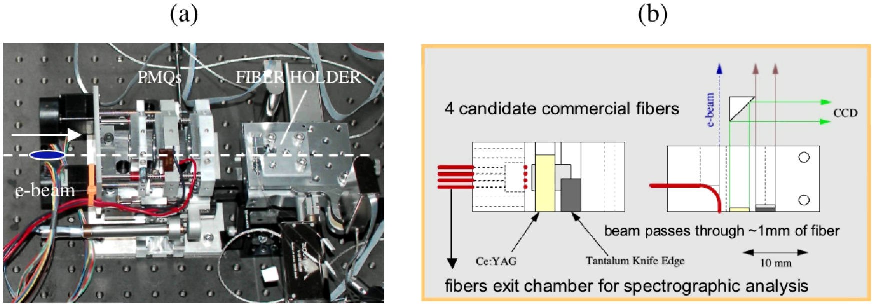

FIGURE 4. Images of (a) the recently installed PMQ and fiber holder assemblies and (b) the fiber holder diagnostic showing attached YAG screen and tantalum knife edge.

a Hamamatsu photomultiplier tube. A Newport model MS260i imaging spectrograph is also on-hand for spectrally analyzing the wakefield radiation, in order to resolve the frequency signatures of fiber modes for comparison with simulations. The energy per electron deposited into a given fiber mode is $\Delta E_{mode} = e^2 c v_g Z_c L/[4(1-v_g/c)\lambda_0^2]$, where Z_c, λ_0, and v_g are the characteristic impedance, wavelength, and group velocity of the mode, and L is the length of fiber [7]. Simulations using the particle tracking code ELEGANT [8] predict an optimal transmission through the fiber core of 50%. So for each electron transmitted through the core, there is an electron that passes through the dielectric lattice, emitting an amount of Cherenkov energy $\Delta E_{Cherenkov} = (1-1/\varepsilon)(4\pi^2 r_e L m c^2 \Delta\lambda)/(f\lambda_0^3)$ [9], where $\varepsilon = 2.13$ is the dielectric constant, $f = 10$ is the air-filling fraction of the lattice, r_e is the classical electron radius, and we take the bandwidth to be equal to the spectrograph resolution ($\Delta\lambda$ = 0.48 nm).

Since the electrons exit through the side of the bent fiber, they pass through a distance $\ell \approx 164$ μm of cladding, contributing an additional factor to the Cherenkov emission which is given by the above relation with $f = 1$ and $L = \ell$. Evaluating the ratio of the two contributions gives the approximate formula

$$\frac{\Delta E_{mode}}{\Delta E_{Cherenkov}} \approx \left[\frac{\varepsilon}{\varepsilon-1}\frac{f\varepsilon_0 c v_g/(c-v_g)}{4\pi(1+2f\ell/L)}\right]\frac{\lambda_0}{\Delta\lambda} Z_c \,. \tag{1}$$

Requiring that this ratio exceed unity imposes a constraint upon the mode impedance: $Z_c[\Omega] > 0.3/\lambda_0[\mu m]$. From Table 1 and the simulation results of the previous section, we see that the Lin fiber satisfies this condition, although the HC-1060 and other commercial fibers studied thus far do not. However, this calculation is somewhat conservative, since it assumes that all Cherenkov radiation emitted will be transmitted to the detector. If a sufficient amount of this radiation radiates out of the fiber or successfully couples to and thereby enhances the accelerating mode, the signal-to-background ratio may be significantly improved. Initial efforts will therefore focus on resolving these questions experimentally by using the commercial fibers to develop a methodology for detecting and characterizing the fiber modes, and as test structures for beam transport studies.

CONCLUSIONS

We have described a program currently underway at SLAC to study the use of photonic bandgap fibers as laser-driven accelerating structures. Simulations of the optimized fiber geometry proposed by X. E. Lin in Ref. [3] show promise, with a well-defined accelerating mode capable of sustaining up to 2.5 GV/m accelerating gradients. Commercially available PBG fibers with lattices similar to the Lin geometry were modeled computationally and found to support accelerating modes, although the on-axis fields are weak at speed-of-light phase velocities. To study these and future candidate fibers experimentally, a test setup at the E-163 beam line has been implemented, using a triplet of permanent magnet quadrupoles to focus the electron beam through the 5 to 10 μm cores of several sample fibers, in order to excite fiber modes whose signatures will then be detected by spectral analysis of the wakefield radiation emitted at the other end of the fiber. Techniques for manufacturing custom-built fibers, optimized for advanced accelerator applications, are being explored in tandem through collaborations with the telecom industry and academia.

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