SIMULATION OF POWER COUPLING AND WAKEFIELD IN PHOTONIC BANDGAP FIBERS FOR DIELECTRIC LASER ACCELERATION*

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Abstract

A photonic bandgap (PBG) lattice in a dielectric fiber can provide high gradient acceleration in the optical regime, where the accelerating mode is obtained from the presence of a single defect in the lattice. In this paper, we will investigate two aspects of the PBG for acceleration. First, the excitation of the accelerating mode can be achieved by directing high-power lasers from free space. Simulation using ACE3P has demonstrated that, by appropriately shaping the end of the PBG fiber, power can be coupled into the fiber using a simple laser configuration. Second, the wakefield generated by the transit of a beam through a PBG fiber will be simulated. The radiation spectrum of the wakefield will be evaluated and corroborated with measurements from a commercial fiber.

INTRODUCTION

The photonic bandgap (PBG) structure proposed by Lin [1] has demonstrated the possibility of confining an accelerating mode in an energy bandgap existing in a periodic lattice of vacuum holes in a dielectric fiber with a central vacuum defect of larger diameter. High accelerating gradient can be achieved in such fibers in the optical regime using lasers for excitation of the accelerating mode. The mechanism of coupling power into the PBG fiber needs to be investigated to ensure efficient excitation of the accelerating mode. Previous studies have shown that a coupling scheme from free space by directly focusing laser pulses in a certain configuration into the fiber can excite the accelerating mode [2]. However, for best results the configuration requires an array of six laser beams arranged in a pattern that obeys the hexagonal symmetry of the Lin lattice. It is desirable to develop improved coupling schemes that can simplify the laser configuration by modification of the existing geometry. It will be shown in the next section that a simpler coupling scheme can be achieved by appropriately shaping the end of the PBG fiber.

While attempts to fabricate Lin-type PBG fibers that can support an accelerating mode are being explored, off-the-shelf telecom fibers are available in the commercial market place, providing samples that can be tested using high energy electron beams at the test facility at SLAC [3]. An example of these commercial fibers is the HC1060 fiber of NKT Photonics which supports the propagation of a telecom mode at the wavelength of 1060 nm. Although the HC1060 fiber does not support a strong TM-like accelerating mode, by measuring the radiated signal after the passage of an electron beam, it is possible to identify the modes that exist in the bandgap of the fiber. In order to corroborate with the measured radiation spectrum obtained from beam tests, simulations have been carried out using the 3D parallel electromagnetic code suite ACE3P [4] to model beam excitation in the HC1060 fiber to calculate wakefield effects and to compare with measurements.

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POWER COUPLING IN LIN FIBER

The Lin PBG fiber consists of circular holes in a hexagonal lattice with spacing *a* between the centers of neighboring holes. The holes have a radius of 0.35*a*. In order to introduce a defect in the lattice, one hole is replaced by another with a radius of 0.52*a*. The material of the fiber has a dielectric constant of 2.13 for this glass at near IR wavelengths. A quarter of the model in the transverse plane is shown in Fig. 1, exhibiting a lattice with hexagonal symmetry and a central defect. The Lin PBG fiber supports a TM-like accelerating mode. For example, the wavelength of the defect mode is 2 μm for a = 2.61 μm. Using ACE3P's frequency domain eigensolver module Omega3P, the calculated longitudinal electric field pattern of the defect mode is shown in Fig. 1. It can be seen that a fairly uniform longitudinal electric field appears in the central circular hole and the field magnitude decays gradually at larger radial distances.

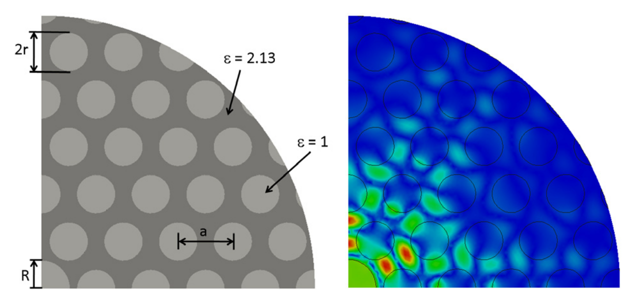

Figure 1: (Left) A quarter model of the Lin PBG fiber; (Right) The longitudinal component of the electric field of the defect mode in the Lin PBG fiber.

The study of power coupling from free space can be carried out through an inverse process by simulating the transmission and radiation of the accelerating mode through a slab of the fiber. The electric and magnetic field patterns calculated by Omega3P are loaded as an excitation at the incident port for ACE3P time domain simulation module T3P. The calculation has been reported in a previous work [2] and has shown that the radiation focuses in six hot spots, which observes the hexagonal symmetry of the Lin fiber. Figure 2 shows the model used in the simulation where a cylindrical slab of the fiber is placed in a hemisphere representing the free

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space. The power on the surface of the hemisphere exhibits the six-fold symmetry of the radiation pattern.

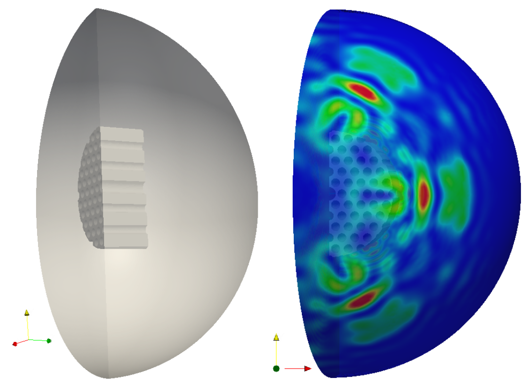

Figure 2: (Left) One half of the model for a cylindrical slab located in free space with the defect mode driven from the left end of the slab; (Right) Radiated power pattern in the forward hemisphere (after reflection at the symmetry plane in the front) with radius of 40λ.

Modification of the above scheme by cleaving the end of the fiber at a certain angle has shown that the far-field radiation pattern changes to a simpler pattern. A model with a cleaved angle of 45^{o} is shown in Fig. 3. By varying the angle gradually, the far-field radiation pattern moves away from its six-fold symmetry without cleaving to focus into two well-defined spots in the upper hemisphere for the slab cleaved with an angle of 45° at the mode exit end. Figure 4 shows the comparison of the far-field radiation for the two cases with and without cleaving. The latter fiber geometry that produces the two hot radiated spots has the potential of simplifying the configuration of laser beams needed to excite the defect mode.

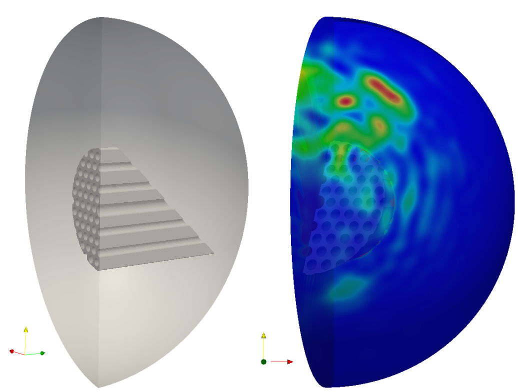

Figure 3: (Left) One half of the model for the Lin fiber slab cleaved at 45^{o} at the exit end of the mode propagation; (Right) Radiated power pattern in the forward hemisphere (after reflection at the symmetry plane in the front) with radius 40λ.

WAKEFIELD IN HC1060 FIBER

The geometry of the commercial HC1060 fiber (KNT Photonics, Denmark) used for telecom was carefully modeled based upon scanning electron micrograph (SEM)

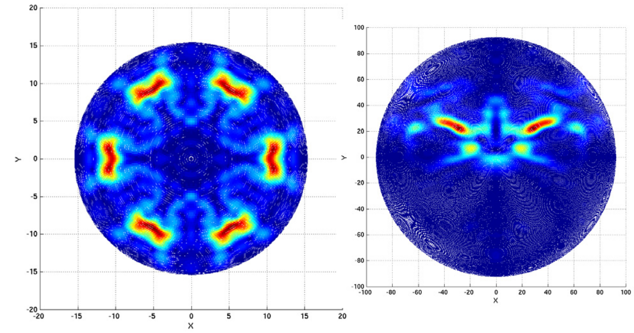

Figure 4: Far-field radiation pattern in the forward hemisphere with radius 80λ for (a) fiber without cleaving showing six-fold symmetry; (b) fiber cleaved at 45^{o} showing two hot spots.

images taken at Stanford University. Figure 5 shows a recent SEM image of a HC1060 sample with ε = 2.13 that was used in the wakefield experiments. The core of the fiber is a circular region, which is the PBG lattice, surrounded by a cladding with a thickness about 2/3 of the diameter of the lattice region. The lattice has a central defect whose size is much bigger than the other lattice holes when compared with the Lin fiber in the previous section. The lattice holes are separated by dielectric vertices and webs whose dimensions are on the order of sub-microns. Simulation using R-Soft BandSolve shows that the web thickness determines the bandgap location with thicker web making lower bandgap frequency. The glass vertices determine the bandgap width, with more glass making wider bandgap. More detailed SEM measurements will be carried out to elucidate more accurately the vertices and web dimensions. For T3P simulation, the lattice period a 2.75 μm, the defect diameter 9.6 μm, the vertex size = 0.16a, and the web thickness = 0.036a have been used.

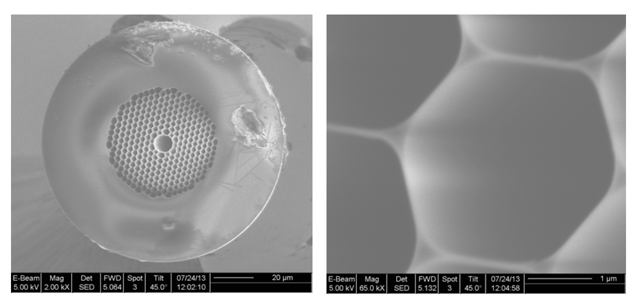

Figure 5: (Left) SEM image of a sample HC1060 commercial fiber; (Right) Close-up image showing the glass webs and vertices connecting the vacuum hexagonal-shape holes.

The T3P simulation of the HC1060 fiber assumes a perfect symmetry of the lattice, so that a 30^{o} slice is sufficient to model the full geometry for the excitation of an axial beam. A Gaussian bunch of RMS σ = 0.3 μm enters from the left boundary and transits through the fiber with a length of 20a. The frequency content of the Gaussian bunch covers the bandgap frequency range as well as that contributed by mostly the cladding modes located near the edge of the fiber. Figure 6 shows a snapshot of the wakefield generated by the transiting beam. The trailing field inside the lattice indicates possible excitation of the fiber modes and the field in the cladding demonstrates Cerenkov radiation because of its higher dielectric constant. The simulated model has a shorter cladding width than that shown in the SEM image. This mostly affects the excitation of the cladding modes. The effect on the lattice modes is small. The radiation field is monitored as a function of time outside the HC1060 structure, from which the mode spectrum is obtained by the Fourier transform of the radiated signal.

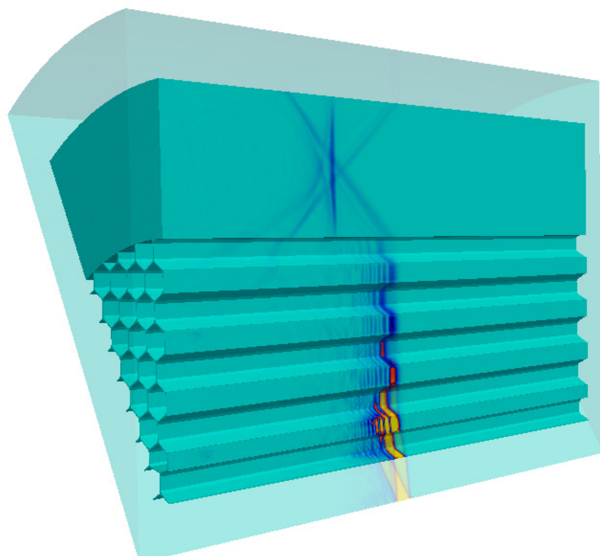

Figure 6: Snapshot of T3P simulation of beam transit through the HC1060 fiber enclosed in a vacuum region. The beam enters the structure from the left end and exits at the right.

Figure 7 shows the comparison of the radiated spectrum obtained by simulation and measurements. The spectrograph measurement in the experimental setup ranges from 550 nm to 1200 nm with 3 nm resolution step, which is comparable to the resolution of the time domain simulation. It can be seen that the simulated spectrum is in good qualitative agreement with measurements. It should be pointed out that modes of lower frequencies (or longer wavelengths) are also found in simulation. They are likely the modes generated in the cladding region of the HC1060 and will radiate away at short distances. The spectrograph measurement can be extended to the lower frequency region to determine whether the cladding modes still contribute to the signal measured at large distance from the beam excitation region.

The modes in the peaks of the spectrum can be identified by calculation in the frequency domain using Omega3P. Figure 8 shows some modes that are localized in the lattice without much field content in the cladding. In particular, a mode with significant longitudinal electric field component is found at 994 nm, which is just outside the bandgap calculated by BandSolve.

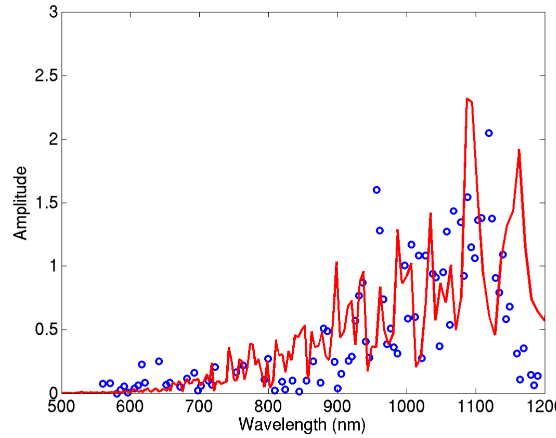

Figure 7: Comparison of simulation (red) and measurements (blue) for the radiation spectrum generated by a beam transit in the HC1060 fiber.

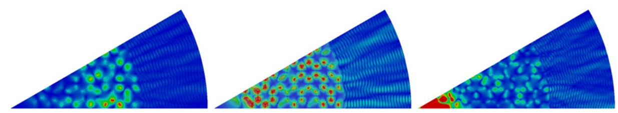

Figure 8: Field patterns of lattice modes in the HC1060 fiber. The wavelengths of these modes are 1150 nm, 1114 nm and 994 nm (from left to right).

SUMMARY

We have used the electromagnetic code suite ACE3P to simulate power coupling and wakefield in photonic bandgap fibers. A simple mechanism of coupling power into the Lin fiber for exciting the accelerating mode can be achieved by cleaving the fiber end at 45^{o} where the laser pulses are directed as indicated in Fig. 4. For the HC1060 commercial fiber for telecom applications, simulation results corroborate well with wakefield experiments, showing that modes in the bandgap can be excited by the transit of a beam through the fiber.

ACKNOWLEDGEMENTS

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