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TOLERANCE STUDIES AND LIMITATIONS FOR PHOTONIC BANDGAP FIBER ACCELERATORS

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Abstract

Laser-driven hollow core photonic bandgap (PBG) fibers were proposed by Lin in 2001 as high-gradient accelerators. The central defect in the transversely periodic lattice supports an accelerating mode for synchronous acceleration in the ultra-relativistic regime. The optical frequencies in such dielectric laser accelerators motivate a sensitivity and tolerance study to overcome manufacturing imperfections. Finally we discuss the propagation characteristics of Lin-fibers and find that small-bandwidth (~ns) pulses would be needed for efficient acceleration over longer distances.

INTRODUCTION

Modern conventional particle accelerators are powered by radiofrequency and use metallic resonant cavities which provides an accelerating gradient of up to ~ 100 MV/m.

Metallic breakdowns and power requirements, as well as the complicated infrastructures of modern accelerators has motivated the scientific community to look for new advanced concepts which could improve accelerating gradients on more compact footprints, i.e. with smaller wavelengths. By comparison, dielectric materials have a laser damage threshold one or two orders of magnitude higher than their metallic counterparts. For example, in the optical regime, fused silica has a breakdown threshold of ~GV/m, the small optical energies required to reach these gradients ~µJ are available at high repetition rates (MHz) from modern conventional laser systems.

The first experimental demonstration of dielectric laser acceleration (DLA) using a dielectric grating-structure was achieved [1–3]. Recently D. Cesar [4] demonstrated a 315 keV energy modulation on a 6.5 MeV beam using an optimized approach. However grating structures are side-coupled and therefore inherently have a very limited interaction time with the accelerating laser pulse. This has motivated alternative research into copropagating accelerating methods.

P. Russell demonstrated the first silica-air photonic crystal fiber (PCF) in 1995 [5, 6]. The PCF consists of a hollow core surrounded by air capillaries which support a photonic bandgap (PBG) preventing the escape of light from the hollow core (defect) via a Bragg-like confinement. The innovative idea to use the PCF as an accelerator was carried out by X. E. Lin [7] who proposed to use the defect for both mode confinement and as an acceleration channel. In his paper he showed that a PBG fiber (Fig. 1) driven by a 1 µm

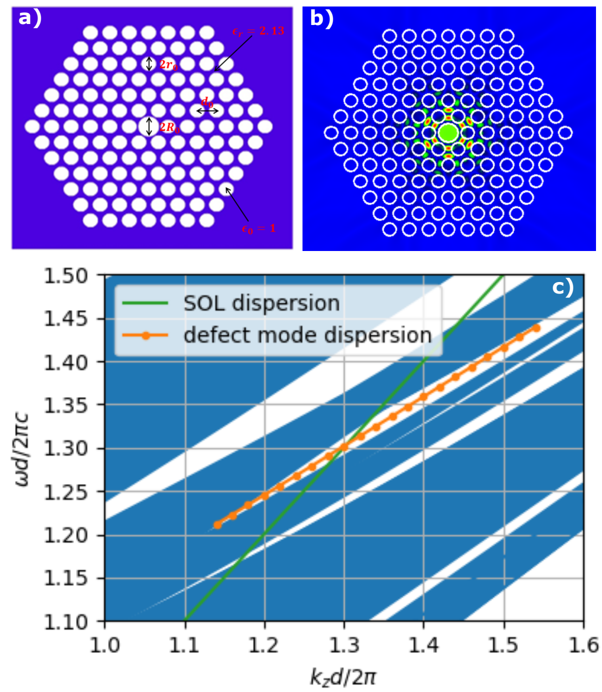

Figure 1: a) Lin photonic bandgap fiber: The accelerating mode, confined by the periodic lattice, propagates in the defect channel. b) CUDOS longitudinal field intensity of the defect mode (color scheme from blue (min) to red (max)). c) Dispersion diagram: the white regions are the bandgap structure of a Lin fiber in a frequency-wavenumber plane. The correct geometrical parameters introduce a defect mode (orange line) that cross the light line (green) in the bandgap.

laser and with specific geometrical parameters, see Table 1, can support a TM_{01}-like mode with a radially uniform longitudindal accelerating field with a phase velocity matching the speed of light.

Synchronous acceleration between the phase velocity of an accelerating mode and velocity of an electron bunch is critical to efficient acceleration – especially in the optical regime. In this paper we investigate the geometrical properties of a PBG fiber. We investigate how the various fiber parameters affect the phase velocity of the accelerating mode. Our simulations are performed using CUDOS MOF, MPB and MEEP. The former is a free code based on the multipole method which uses Fourier-Bessel expansion centered on each fiber hole to enforce boundary conditions [8]; the second one is a frequency-domain eigensolver which computes definite-frequency eigenstates in periodic dielectric struc-

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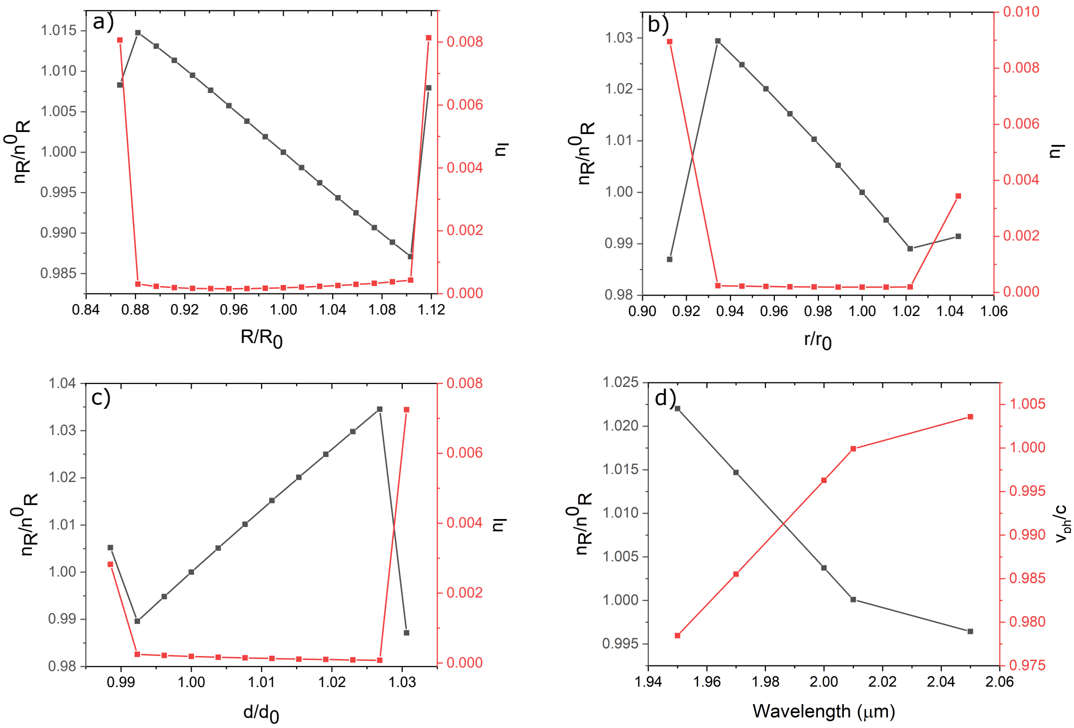

Figure 2: a)-c) Real and imaginary components of the effective refractive index as function of the geometrical parameters. The linear correlation results in a tolerance range of 10% in which the fiber supports an accelerating mode. d) Real part of the defect mode's effective refractive index and phase velocity as function of wavelength.

Table 1: Geometrical Parameters of the Lin Fiber Using a 2 μm Laser

Lin's fiber Parameter	
Defect radius (R_0) [μm]	1.3572
Capillaries radius (r_0) [μm]	0.9135
Pitch (d_0) [μm]	2.61
Dielectric permittivity (ϵ_r)	2.13
Effective refractive index (n_R^0)	1.00369

tures for arbitrary wavevectors [9]; while the latter one is a finite-difference time-domain (FDTD) method for computational electrodynamics [10]. The high-frequency driving fields and scale of the accelerating structures suggests challenging tolerance requirements and motivates a rigorous investigation.

SIMULATION RESULTS

A 2D PBG has a periodic structure in the transverse directions, providing mode confinement, and is uniform in the longitudinal direction. Due to the multiple scattering of the electromagnetic waves which occur at each vacuum-dielectric interface, a forbidden energy gap (bandgap) can appear in the dispersion diagram. Figure 1 shows the band diagram of a Lin-fiber obtained from MPB simulations for the geometrical parameters detailed in Table 1.

A deeper understanding of a PBG is based on the Floquet-Bloch's theorem and the variational principle [11–13]. The bandgap width is primarily due to the contrast between the permittivities of the dielectric and vacuum-capillaries in 1D. However in 2D, the bandgap width is determined by a combination of the permittivity contrast and geometrical parameters which can tune the effective refractive index of the mode $n_{\text{eff}} = n_R + i\, n_I$ where i is the imaginary unit. The real component describes the phase velocity, v_{ph}, of the mode

$$n_R = c/v_{\text{ph}}\,, \tag{1}$$

where c is the speed of light, while the imaginary part represents the diffractive loss due to Poynting flux escaping in the transverse direction

$$n_I = \alpha/2k_z\,, \tag{2}$$

where α is the loss coefficient and k_z is the propagation constant in the material [14].

Another important figure of merit is the Q-factor for the mode which is linked to its bandwidth:

$$Q = f_r/\Delta f\,, \tag{3}$$

where f_r is the resonant frequency and Δf is the mode's bandwidth.

To accelerate particles efficiently, the phase velocity v_{ph} of the confined TM-like mode must match the electron velocity. In the ultrarelativistic regime, where $v_{\text{ph}} \to c$, the

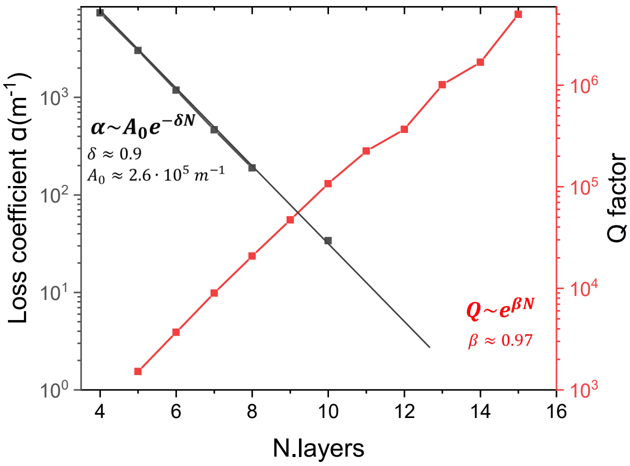

Figure 3: Loss coefficient and Q-factor as function of number of layers in a log-scale plot.

longitudinal accelerating fields in the core become transversely uniform. If the geometric parameters (e.g. defect radius, capillary radii and pitch) change then the mode will shift in the dispersion diagram, yielding a new v_{ph}, (Eq. 1).

Figure 2 (a-c) show the behavior of n_{eff} while scanning each parameter independently. To study the change in n_{eff} we have used CUDOS and within the range where it shows a linear relation to the defect radius we find that $d(n_R/n_R^0)/d(R/R_0) = -0.13$ in agreement with the literature [14]. The linear trend is also present as we modify the underlying crystal. By scanning the radius and pitch of the capillaries we find $d(n_R/n_R^0)/d(r/r_0) = -0.47$ and $d(n_R/n_R^0)/d(d/d_0) = 1.3$, respectively. We note that the mode dispersion line is strongly dependent on the capillary radii and the pitch rather than the defect radius.

Finally, a rough trend of n_{eff} as function of the input laser wavelength has been presented in Fig. 2(d). The possibility to shift the phase velocity of the mode by tuning the wavelength may be a useful tool to select the right n_{eff} to accommodate manufacturing imperfections. In the n_R linear range, the fiber supports an accelerating mode of which n_I is about 2×10^{-4}, which corresponds to a very large loss coefficient, α (see Eq. 2).

Figure 3 shows that the confinement could be improved as we increase the number of surrounding layers. The exponential decay behavior of the loss coefficient leads to an improvement of the Poynting flux confinement and thus could increase the length of the fiber (neglecting the phase slippage)

$$S_z \approx e^{-\alpha z}\,. \tag{4}$$

There is a tradeoff between the loss coefficient and quality factor. It is crucial to note that as the number of layers increases, the loss factor becomes exponentially better (Fig. 3); however, with additional layers, the mode bandwidth also decreases exponentially. This implies that efficient acceleration in a Lin fiber is incompatible with short, high bandwidth laser pulses. From Fig. 3, for a loss factor of α=1/m, we would require ~12 layers, suggesting an associated quality factor of 300,000. This corresponds in turn to a transform limited pulse duration of 880 ps for a Gaussian pulse. The SINBAD facility at DESY [15] will begin research on DLA after commissioning is complete. The 2 µm laser system employed for these experiments has a transform limited pulse duration of 1.25 ps, which corresponds to 350 GHz of bandwidth. To gain some insights with the compatibility of a Lin fiber, Eq. 3 yields a Q-factor of ~450 which corresponds to an α ~ 1100 m^{-1} for 6 layers. Taking into consideration Eq. 4, 70% of the incoupled power will be lost into the matrix along a 1 mm long structure.

CONCLUSIONS AND OUTLOOK

In this paper we have presented a tolerance study assuming realistic manufacturing imperfections and showing that the geometrical PBG fiber properties play a crucial role for getting and confining the optimal accelerating mode into the defect. Moreover, we find a tolerance range of 10% in which the mode properties in the fiber can be recovered by tuning the laser wavelength. Finally, we have pointed out that a strong limitation of a Lin-fiber is the tradeoff between the loss coefficient and allowed bandwidth of the accelerating mode. An investigation into the compatibility of Lin fibers with narrowband ~ns pulses could be very interesting; however, we have shown that efficient acceleration using short, high bandwidth pulses in Lin-fibers is incompatible.

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