Simulation of Tapered Co-propagating Structures for Dielectric Laser Accelerators

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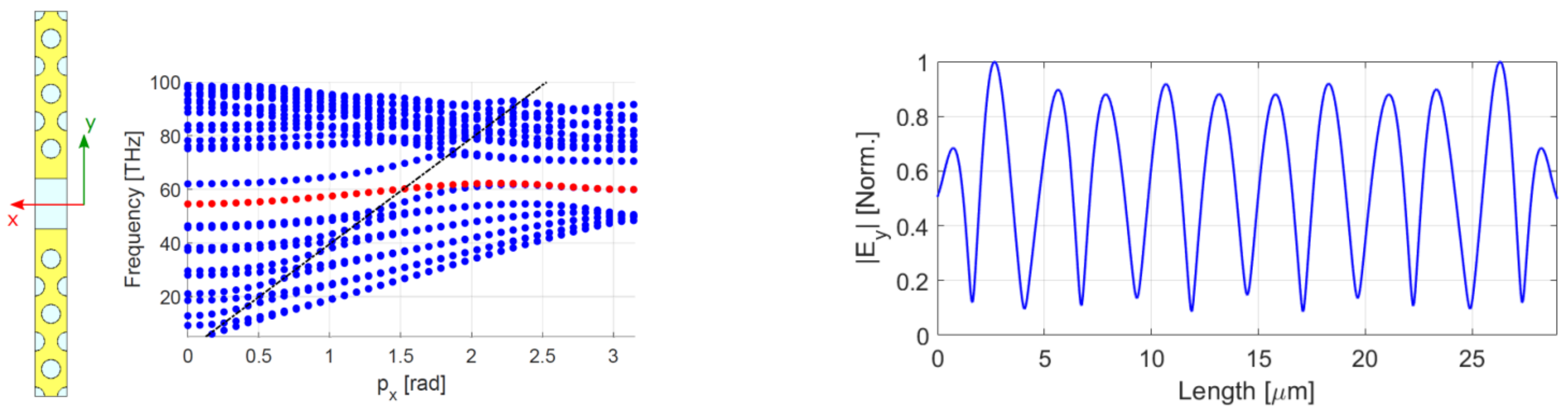
Introduction

- **Enhancing Compactness and Efficiency**: By utilizing laser pulses and advanced dielectric materials, this emerging technology holds the promise of delivering particle acceleration systems that are not only more compact but also significantly more efficient and cost-effective than conventional accelerator technologies.
- **Exploring Innovative Approaches**: Within the realm of accelerator research, one particularly promising avenue is the investigation of hollow-core dielectric Electromagnetic Band Gap (EBG) microstructures powered by lasers. These structures represent an exciting and novel frontier in accelerator science.
- **Comparative Advantages**: In contrast to traditional metallic accelerators, dielectric accelerators offer several key advantages. They possess higher damage thresholds and can support greater accelerating gradients, particularly in the GV/m regime, outperforming their metallic counterparts.
- **Foundation in Photonic Crystals**: Dielectric Laser Accelerators are fundamentally grounded in the principles of Photonic Crystals (PhCs). PhCs are structures engineered to either permit or obstruct the propagation of electromagnetic waves within specific frequency bands [1].
- **Diverse Accelerating Structures**: The versatility of dielectric laser accelerators is reflected in the variety of structures that can be employed, including 2D or 3D accelerating waveguides based on different PhC configurations, as well as dielectric slot waveguides.
- **Numerical Insights**: Valuable insights into the performance of these accelerators have been gained through electromagnetic mapping and Particle-in-Cell (PIC) simulations, carried out using advanced software like CST Studio Suite. These simulations have enabled the extraction of several critical figures of merit.
- **Expansive Applications**: Beyond the realm of particle physics, dielectric laser accelerators have the potential to revolutionize a multitude of fields, ranging from medicine and industry to scientific research and space exploration. As research in this exciting field continues to advance, we can anticipate the emergence of even more compelling applications.

Dielectric waveguides

2D Accelerating waveguides based on triangular lattice PhC (β=1)

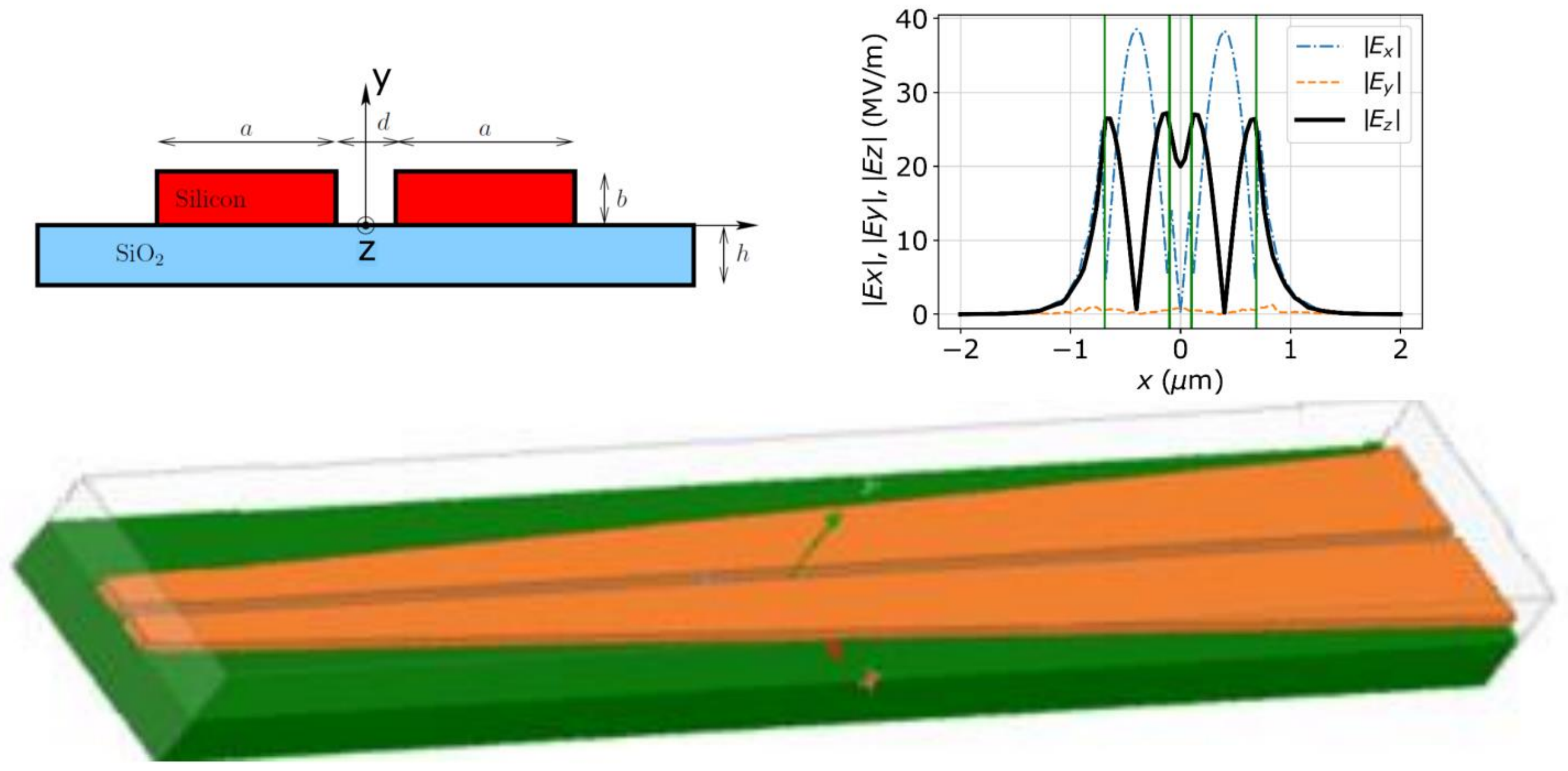
- Based on a 2D triangular lattice PhC, composed of periodically arranged vacuum holes with radius r = 0.3d, where d is the lattice constant (distance between two adjacent vacuum holes center) equal to 1.207 μm, practiced on a slab ($\varepsilon_r = 9.7$). Dimensions depends on operating wavelength.
- The central vacuum channel, called "defect", has been tuned to support an accelerating mode, synchronous with the speed of light at the operating frequency of 60 THz.



(left) 2D triangular lattice waveguide supercell and projected band diagram along the accelerating x axis. The TM01-like mode (red curve) is synchronous with the speed of light at f0 = 60 THz. (right) Accelerating Ey field component along waveguide axis, for a structure of 29 μm total length.

Slot waveguides (0.4<β<0.7)

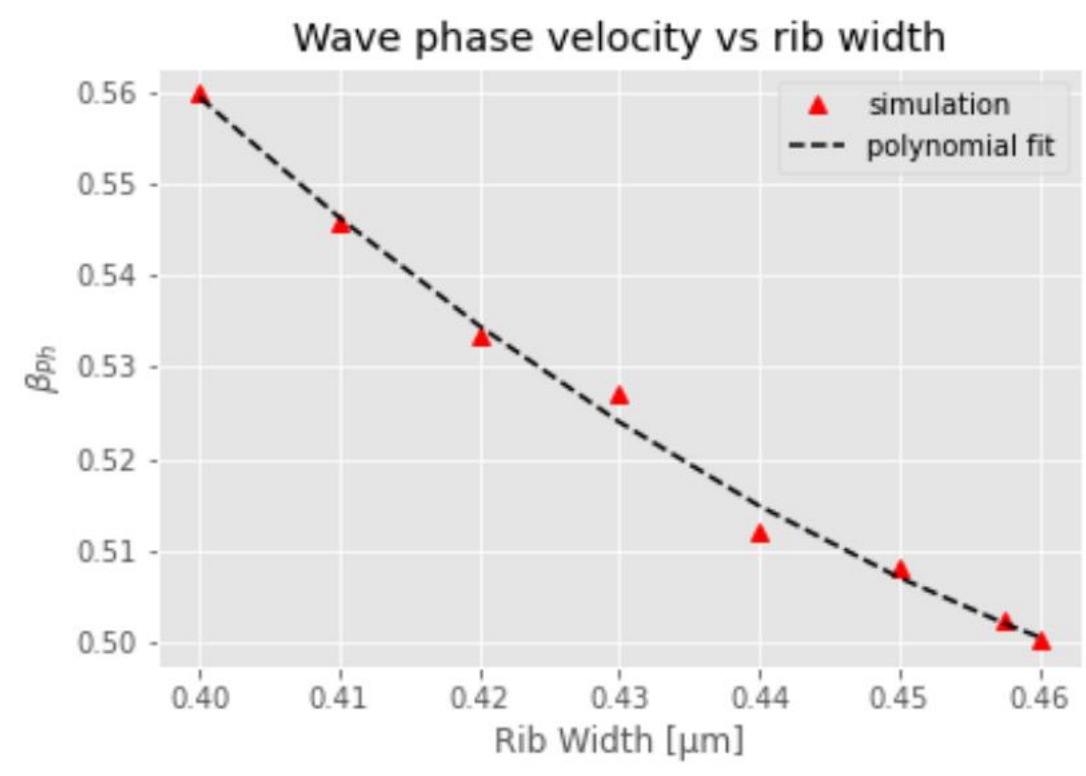
- The slot waveguide, is a dielectric structure employed for sub-relativistic electron acceleration.
- It supports a longitudinal accelerating field whose phase velocity can be tuned to maintain the synchronism with the accelerated electrons as they gain velocity [2].
- It consists of two silicon tapered "rib" waveguides of width a = (0.4575-0.44345) μm and height b = 0.172 μm supported by a SiO2 substrate, separated by a hollow-core channel of width d = 0.155 μm. Accelerator length is L = 20 μm.
- The accelerating mode is excited by a 1.55 μm laser with input power P_{inj} = 250 W.



Slot waveguide cross section (upper-left) and electric field components (upper-right) |Ex |, |Ey |, |Ez | along x (at y = b/2). On waveguide axis (x = 0) the longitudinal accelerating field component, |Ez |, is large with respect to the transversal ones |Ex | and |Ey |. (Bottom) A schematic representation of the rib's tapering for synchronous condition

Tapering: Phase velocity vs Rib width

- Phase velocity depends on rib width. The corresponding pair values were calculated by performing a parametric sweep in time domains simulations [2].
- Electrons traveling along the accelerator increase their velocity as they gain energy.



Phase velocity corresponding to different values of the rib width. It is calculated by fixing all the structural fields and extracting their phase velocity for each value of a.

- Particle phase dictates the interaction between the electron and the EM field.
- Synchronous condition is given by $v_{ph} = v_e$.
- With adequate tapering of the slot waveguide, phase velocity can match the electron velocity, providing maximum energy gain during the acceleration stage as a result

$$E_z(z,t) = E_0 \cos(\varphi)$$

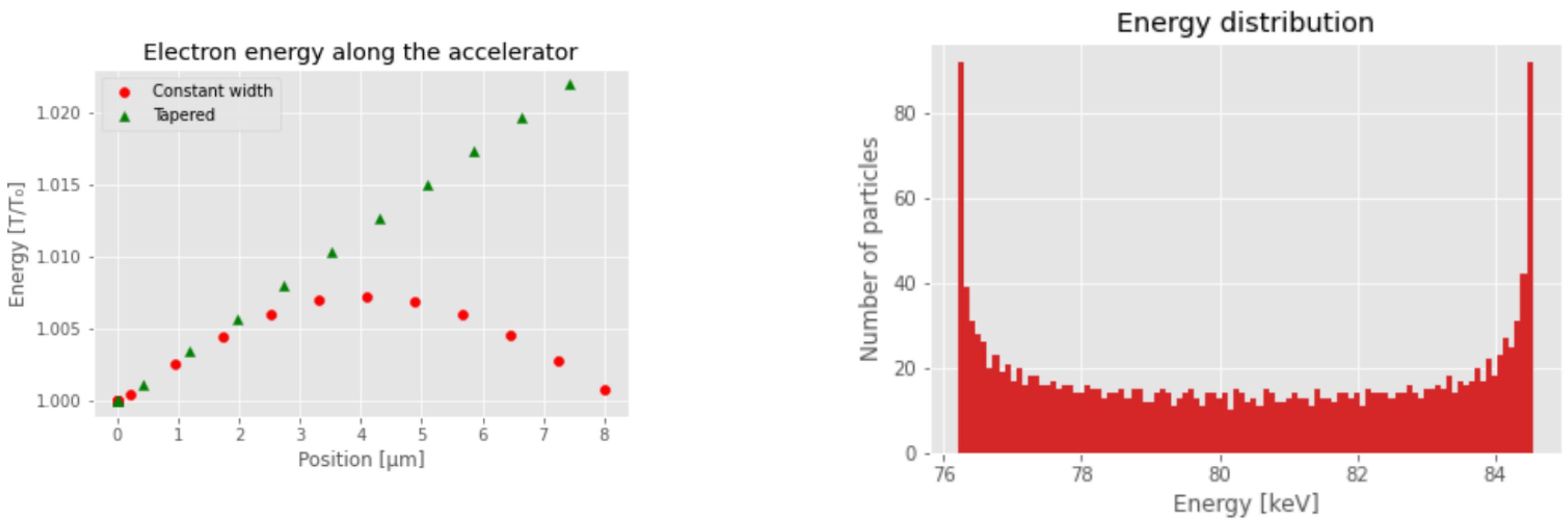
where φ is given by:

$$\varphi = \omega\left(t_0 + \int_0^z \frac{dz'}{v_e(z')} - \int_0^z \frac{dz'}{v_{ph}(z')}\right) + \varphi_0$$

The electric field seen by the electron is given by a sinusoidal dependence. The phase plays a fundamental role in the acceleration.

Beam dynamics

- An electron source with initial energy To = 80 keV is placed at the beginning of the DLA
- Performance comparison: Tapered vs non-tapered slot waveguide. Tapered delivers continuous acceleration. Its counterpart fails at this task due to its constant phase velocity.
- In a DC source, the particles exiting energy distribution varies according to the initial phase. Particles close to the resonant phase increase their energy up to 5 keV. Dissimilar phases decelerates the electrons, losing some part of their kinetic energy in the process.



Left: Electron energy according to the position inside the accelerator for a tapered and non-tapered (constant width) slot waveguide. Right: Energy distribution at the exit of the accelerator for a continuous monochromatic source.

Figures of Merit

- The acceleration gradient is around 227 MV/m, which is above current conventional accelerators
- The total energy gain is 4.5 keV in 20µm.
- $\Delta W = -eE_0 L\cos(\varphi)$

Conclusions and Perspectives

- Two different DLA structures has been presented for electron acceleration for both sub-relativistic and relativistic regime.
- Tapered slot waveguide proves to be a potential tool for sub-relativistic electron acceleration. By adapting its structural parameters, a wide range of electron energies can be covered
- Phase acceptance and two-stages acceleration schemes are next step

References

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