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Numerical design of novel synchronous waveguides for Dielectric Laser Accelerators

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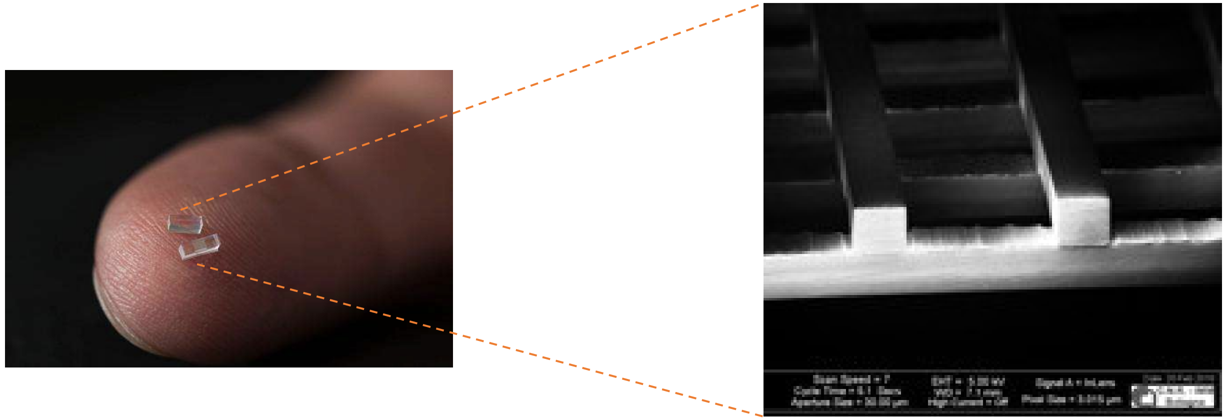

4th International Workshop on "Ultrafast Beams and Applications", 17-23 June 2024, CANDLE, Armenia

Summary

- Dielectric Laser Accelerators: introduction
- Co-propagating dielectric structures
- Beam-dynamics simulation results and fabrication tests
- Conclusion and perspectives

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Dielectric Laser Accelerators (DLA) : introduction

- **MOTIVATION**: strong need of particle accelerators working at higher and higher frequencies ($\lambda = 2$ or $5\ \mu m$) to obtain high energy particle beams and **high accelerating gradient** for **research and medical applications**.

- Conventional radio frequency (RF) metallic accelerators are not suitable for the task because of electrical breakdown in metals and their high losses at high frequencies.

SOLUTION: employing dielectric structures

Main advantages of DLA:

a) larger damage threshold of dielectrics near infrared with respect to metals;

b) with the same maximum electric field, **shorter wavelength means higher *accelerating gradients per unit length*;**

c) consequential **reduction of size and fabrication costs.**

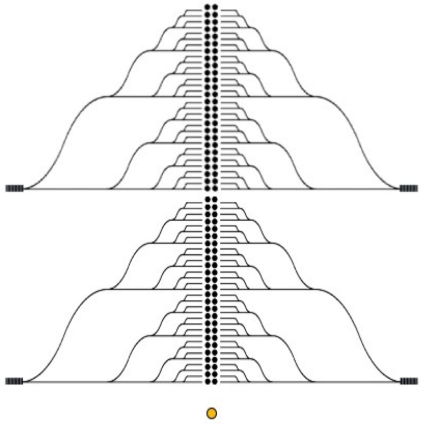
- Compact DLAs are possible by employing Electromagnetic Band Gap (EBG) structures based on the photonic crystals.

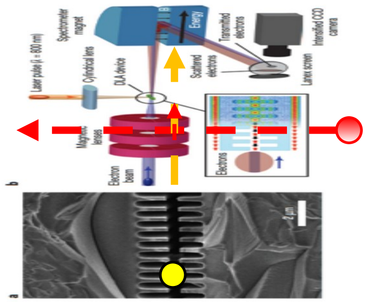
Dielectric Laser Accelerators (DLA) : introduction

Cross-propagating schemes

side-pumped configurations
Power Delivery

[Tyler W. Hughes et al. Phys. Rev. Applied, 9:054017, 2018]





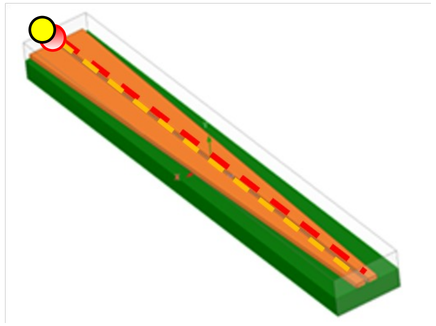
- require a complex **2D feeding** network with a **large footprint proportional to L^2**
- Not very efficient in terms of length effectively employed for particle accelerations

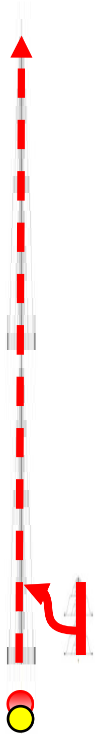
Laser
Particle

Copropagating schemes

CW collinear hollow-core scheme
Power Delivery

✓ guiding structure
✓ field confinement
✓ Strong longitudinal field component



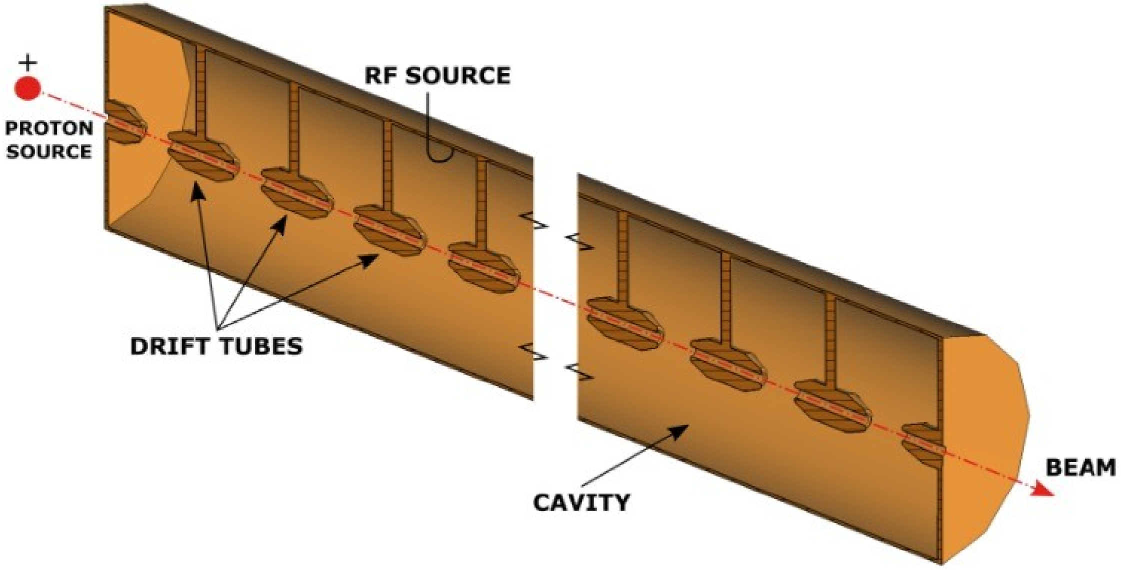


- based on hollow-core waveguides
- reaching a final energy **scales linearly with the structure length L**

Dielectric Laser Accelerators (DLA) : introduction

1 M€

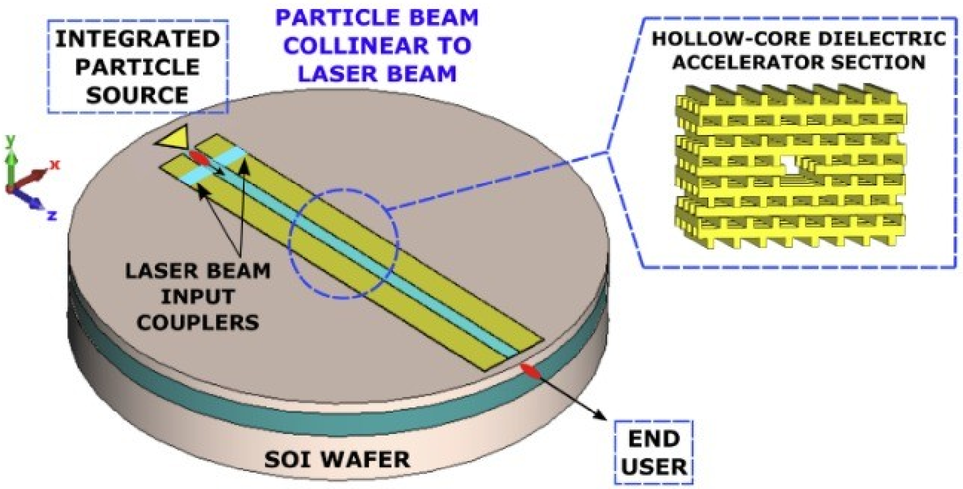
CONVENTIONAL ACCELERATOR



Total length ~ 100 m

Envisaged DLA structure

10 k€



Total length ~ 10 cm

Summary

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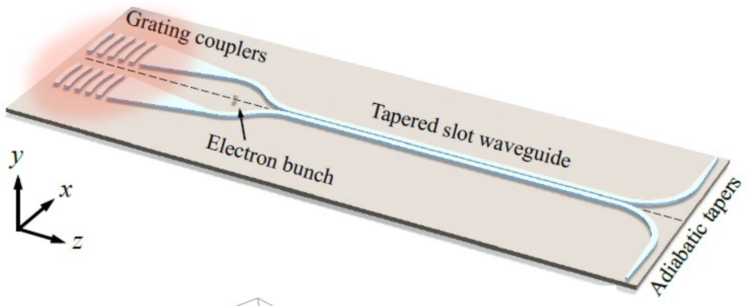
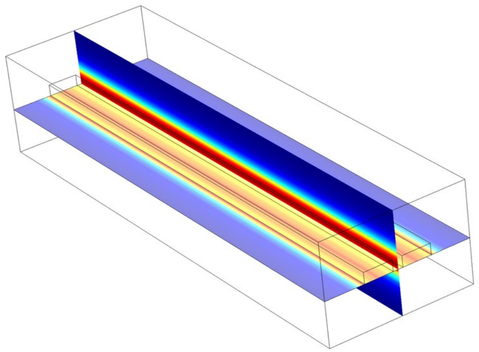
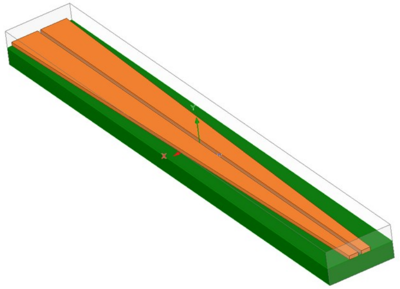
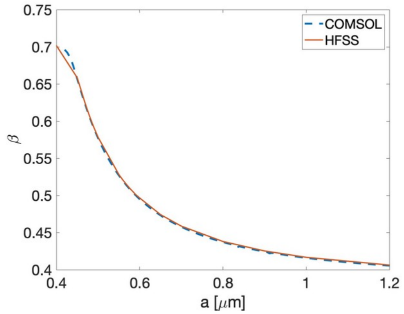
Copropagating schemes for Dielectric Laser Accelerators

1) Slotted waveguide @ 2 µm
[]

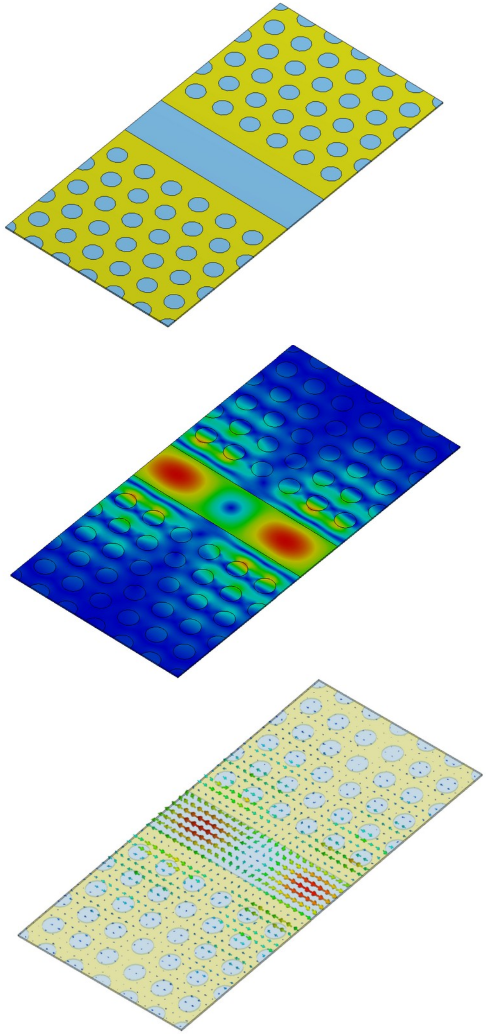




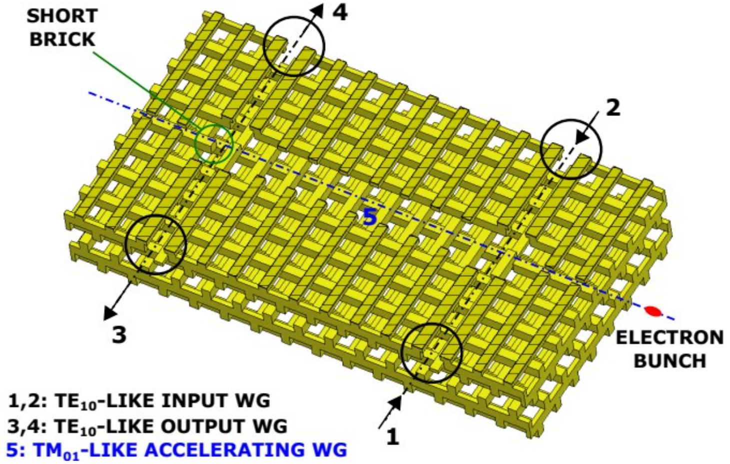


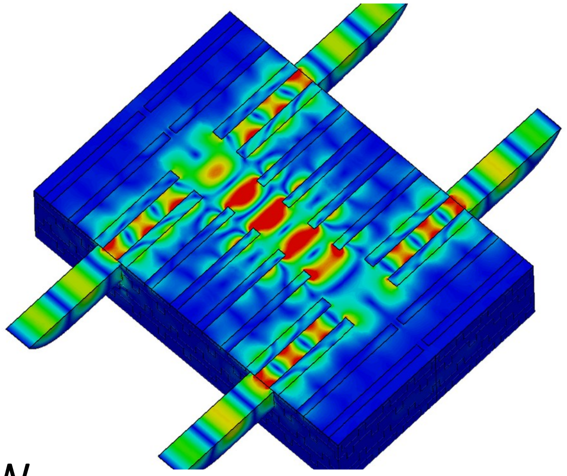


2) 2D PhC waveguide @ 5 µm
[



3) Woodpile @ 5 µm
[]

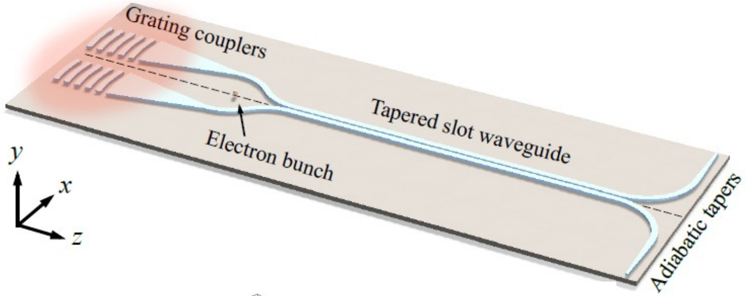


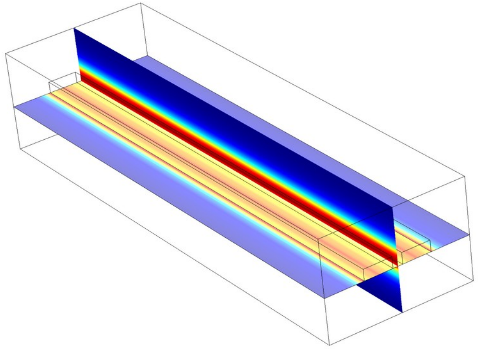


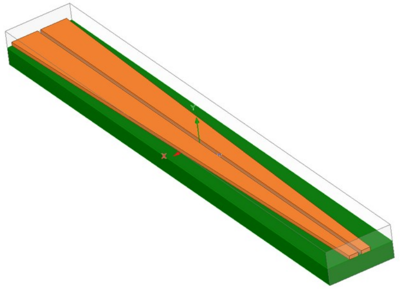
1 GV/m
@ P_{INJ} = 500 W

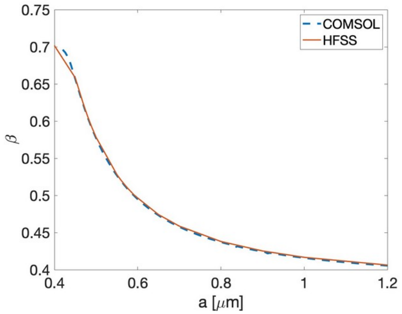
Copropagating schemes for Dielectric Laser Accelerators

1) Slotted waveguide @ 2 µm
[=1.5 k]









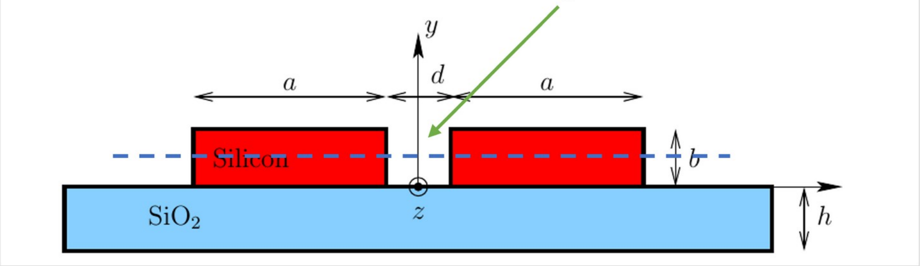
2) 2D PhC waveguide @ 5 µm
[

3) Woodpile @ 5 µm
[]

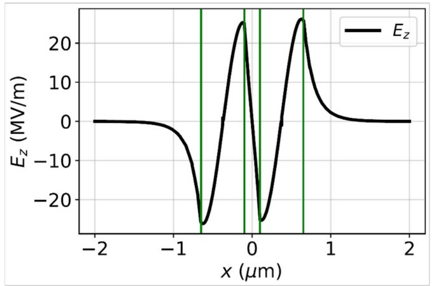
1 GV/m
@ P_{INJ} = 500 W

Slotted waveguide

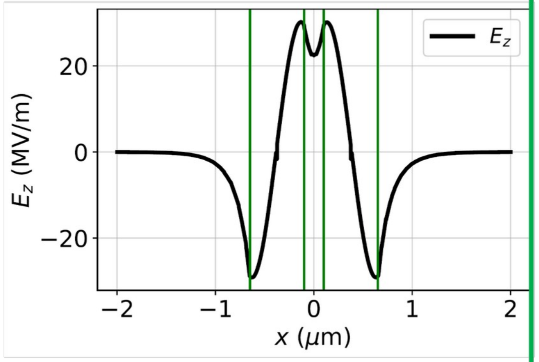
- High-index (silicon) strips separated by a small gap
- Fundamental (even) mode, accelerating (odd) mode
- Selective excitation of the accelerating mode
- Tuning of cross section to synchronize <u>sub-relativistic</u> particles



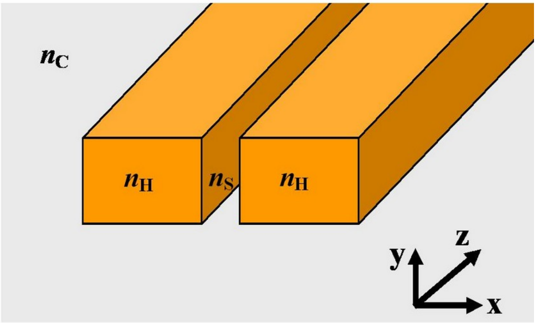
"Fundamental" mode - electric field Ez component (even symmetry)

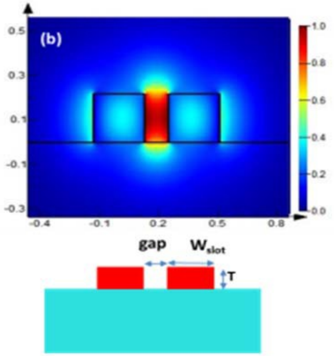


"Accelerating" mode - electric field Ez component (odd symmetry)



Schematic of a slot waveguide





Zhao et al., "Design of a tapered slot waveguide dielectric laser accelerator for sub-relativistic electrons"; 2018

Slotted waveguide

Synchronicity: for a varying particle velocity, we need a <u>non-uniform slot waveguide</u>

Electron traveling
with velocity $v_e(z)$

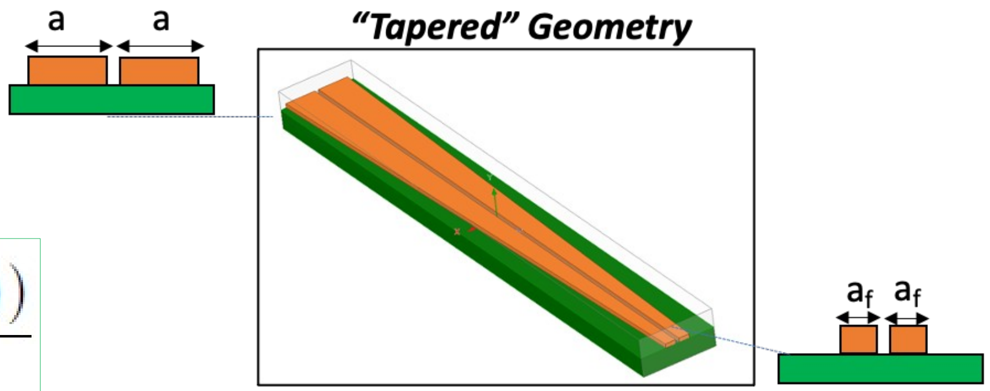
$$\Delta W = -eE_0 \int_0^{L_{acc}} \cos\left[\omega\left(t_0 + \int_0^z \frac{dz'}{v_e(z')} - \int_0^z \frac{dz'}{v_\phi(z')}\right) + \phi_0\right] dz$$

SYNCHRONOUS CONDITION IS FULFILLED WHEN:

$$\frac{v_e(z)}{c} = \beta_e(z) = \beta_\phi(a(z)) = \frac{v_\phi(a(z))}{c}$$

$$a = a(z) \quad \text{s.t.} \quad \beta_\phi(a(z)) = \beta_e(z)$$

"Tapered" Geometry



<u>non-uniform slot waveguide</u>

Slotted waveguide: physics-based design

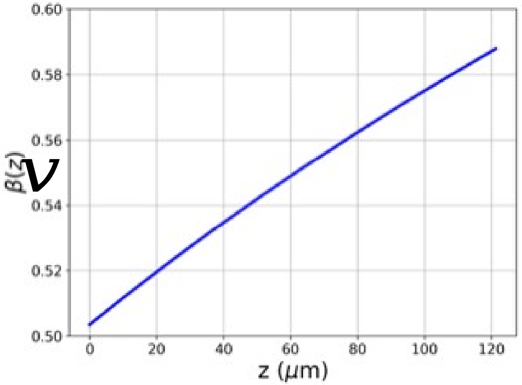
STEP 1: Relativistic dynamic evaluation

$$\Delta W = q\int_0^L E_z(z,t)dz = q\int_0^L E_0 \cos\left\{ \omega\left[\int_0^z \frac{1}{v_{\text{part}}(z')}dz' - \int_0^z \frac{1}{v_{\text{ph}}(z')}dz'\right] \right\} dz$$

=1 for ΔW maximization

$E(z,t)=E_0$ @ 1st STEP 1

$$\begin{cases} \dfrac{dp}{dt} = qE(z,t) \\ \dfrac{dz}{dt} = \dfrac{p}{\sqrt{\frac{p^2}{c^2}+m_0^2}} \end{cases} \rightarrow p(z,t) \rightarrow v$$



Theoretical ideal BD result

Slotted waveguide: physics-based design

STEP 2: Derivation of a calibration curve

$$\Delta W = q\int_0^L E_z(z,t)dz = q\int_0^L E_0 \cos\left\{ \omega\left[\int_0^z \frac{1}{v_{part}(z')}dz' - \int_0^z \frac{1}{v_{ph}(z')}dz'\right]\right\} dz$$

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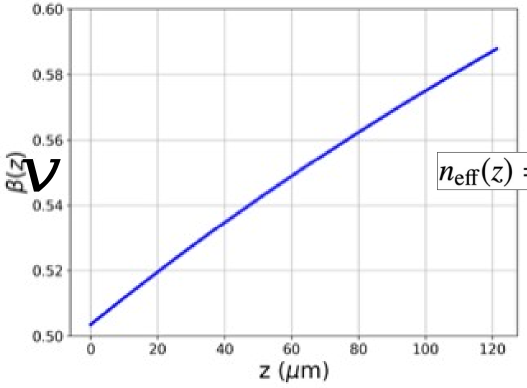
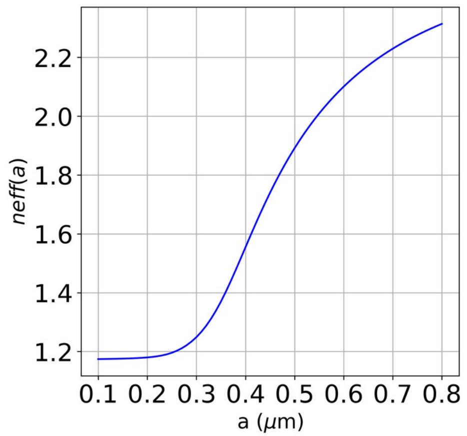


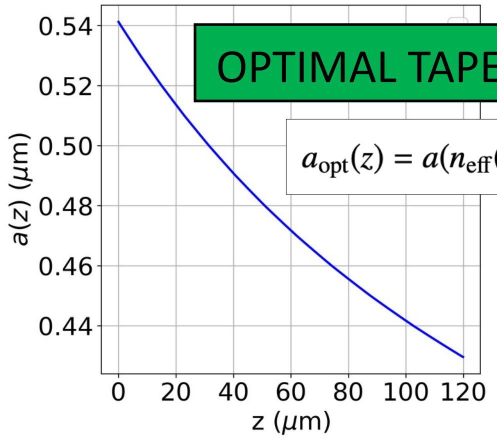
$n_{eff}(z) = 1/\beta(z)$

Theoretical ideal BD result

parametric study in COMSOL

Calibration Curve





$a_{opt}(z) = a(n_{eff}(z)) = a(\beta(z))$

Slotted waveguide: physics-based design

$$\Delta W = q\int_0^L E_z(z,t)dz = q\int_0^L E_0 \cos\left\{ \omega\left[\int_0^z \frac{1}{v_{part}(z')}dz' - \int_0^z \frac{1}{v_{ph}(z')}dz'\right] \right\} dz$$

=1 for ΔW maximization

$E(z,t)=E_0$ @ 1st STEP 1

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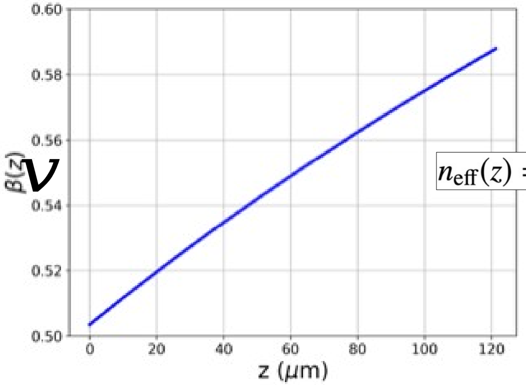
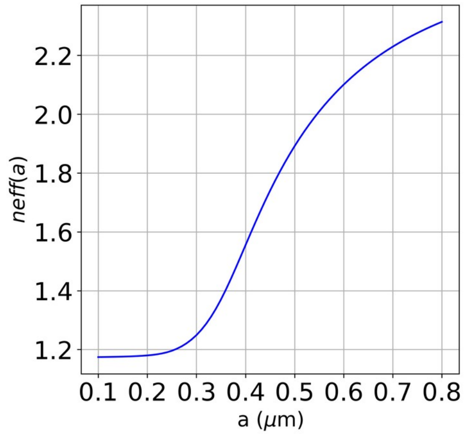


$n_{eff}(z) = 1/\beta(z)$

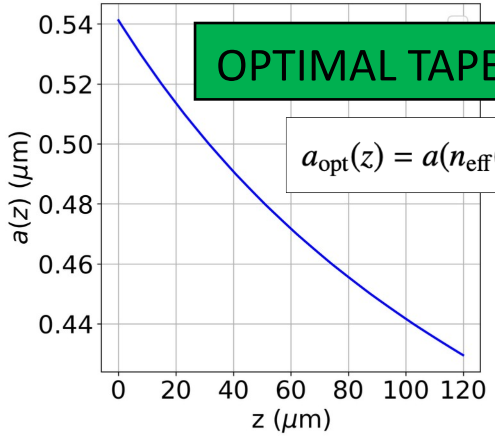
Theoretical ideal BD result

parametric study in COMSOL

Calibration Curve



OPTIMAL TAPER



$a_{opt}(z) = a(n_{eff}(z)) = a(\beta(z))$

$E(z,t)$

STEP 3: Testing of the taper (3D) through EM COMSOL simulation

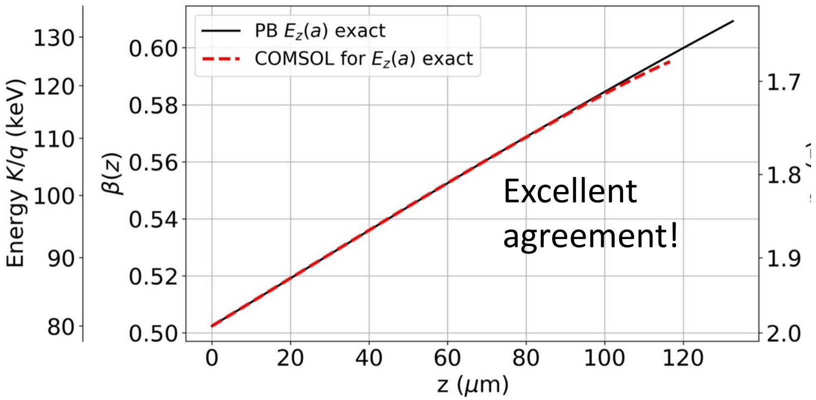
Slotted waveguide: physics-based design

STEP 1: Relativistic dynamic evaluation

$$\Delta W = q\int_0^L E_z(z,t)dz = q\int_0^L E_0 \cos\left\{ \omega\left[\int_0^z \frac{1}{v_{part}(z')}dz' - \int_0^z \frac{1}{v_{ph}(z')}dz'\right] \right\} dz$$

=1 for ΔW maximization

$$\begin{cases} \frac{dp}{dt} = qE(z,t) \\ \frac{dz}{dt} = \frac{p}{\sqrt{\frac{p^2}{c^2}+m_0^2}} \end{cases}$$

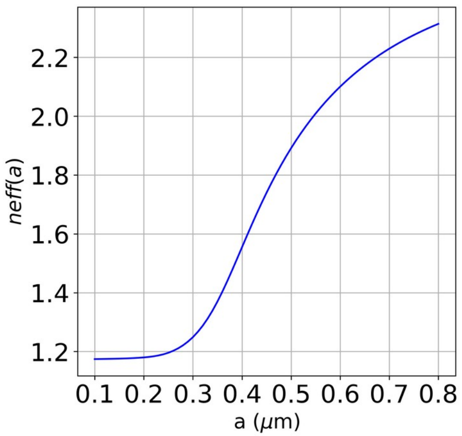


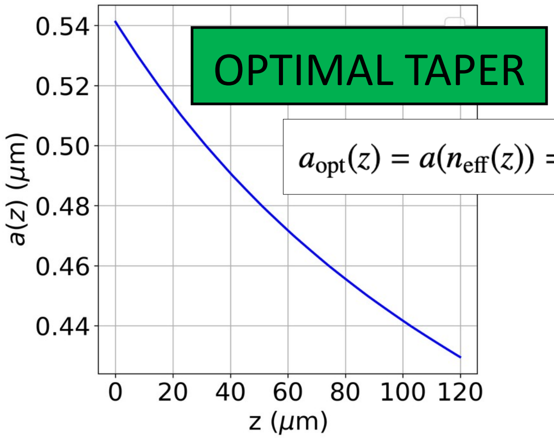
-Theoretical ideal vs ---Numerical BD result

STEP 2: Derivation of a calibration curve

parametric study in COMSOL

Calibration Curve





$$a_{opt}(z) = a(n_{eff}(z)) = a(\beta(z))$$

$E(z,t)$

STEP 3: Testing of the taper (3D) through EM COMSOL simulation

Slotted waveguide: summary

[Palmeri, R., et al. "Optimization of sub-relativistic co-propagating accelerating structures." *Optics Express* 31.23, 2023.]

In formula:

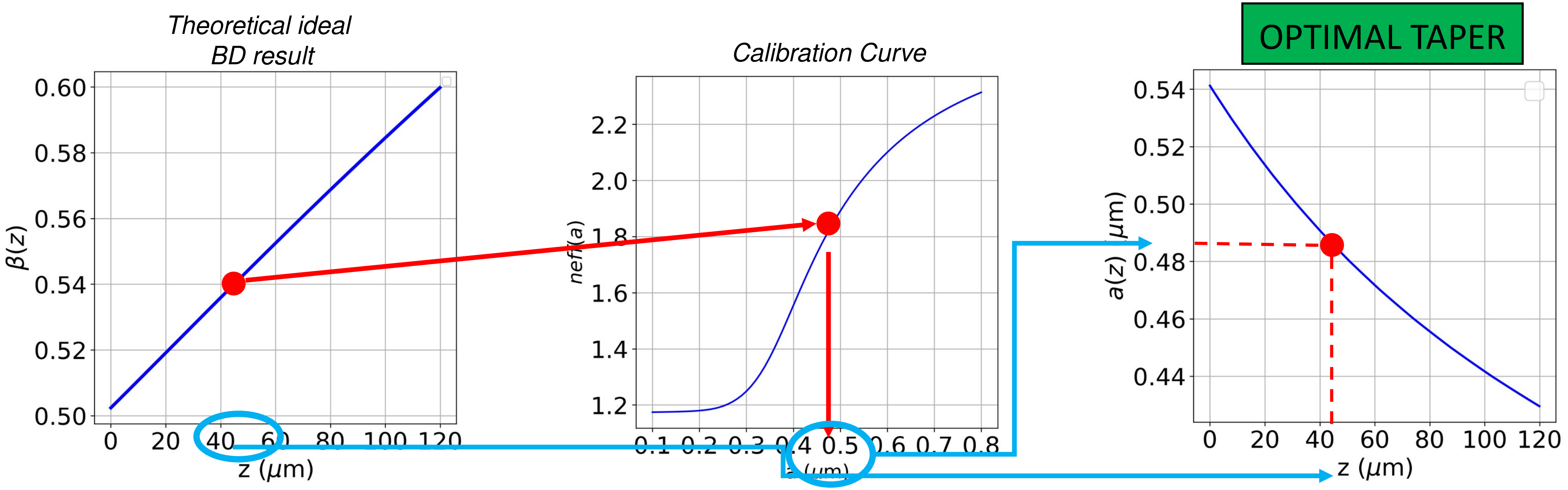
$$E_z(z,t) = E_0 \cos\left[\omega t - \int_0^z k_z(z')dz'\right]$$

Accelerating field

$$\Delta W = q\int_0^L E_z(z,t)dz = q\int_0^L E_0(z')\cos\left\{\omega\left[\int_0^z \frac{1}{v_{\text{part}}(z')}dz' - \int_0^z \frac{1}{v_{\text{ph}}(z')}dz'\right]\right\}dz$$

Energy gain

=1 for maximization



Copropagating schemes for Dielectric Laser Accelerators

1) Slotted waveguide @ 2 µm

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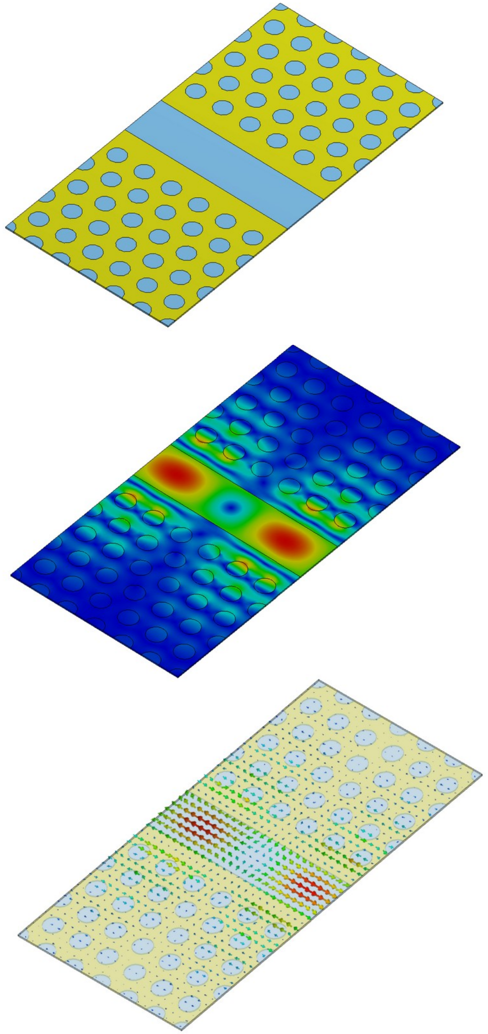
2) 2D PhC waveguide @ 5 µm

[



3) Woodpile @ 5 µm

[]

1 GV/m

@ P_{INJ} = 500 W

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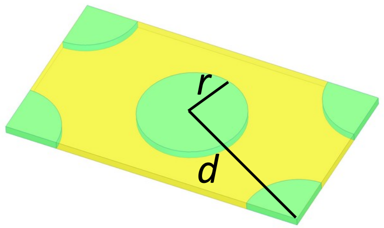
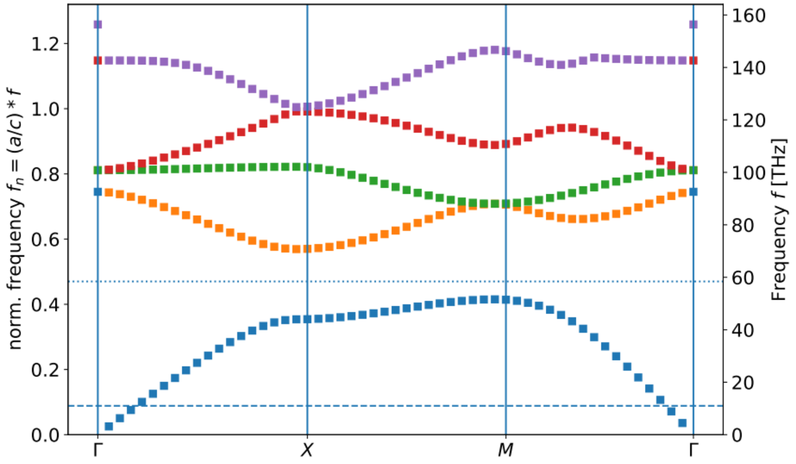
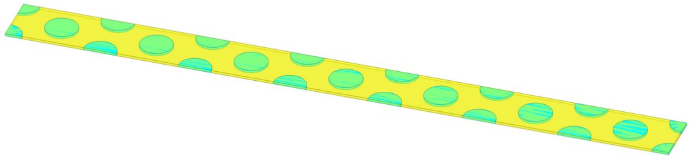
2D photonic crystal waveguide

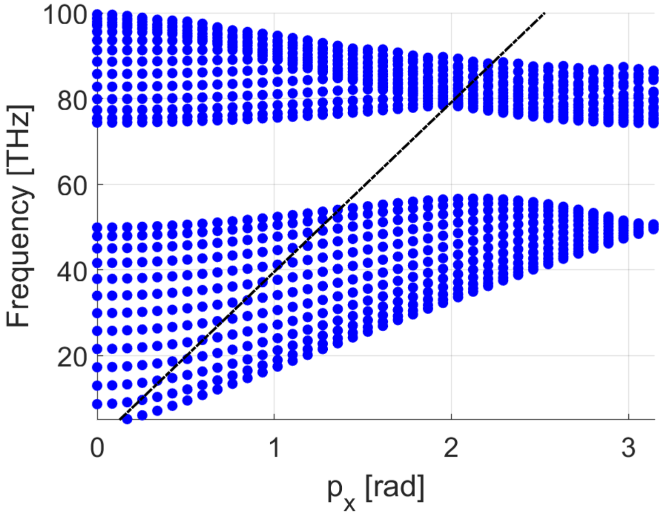
a) computation of the **band diagram** of the triangular lattice primitive cell



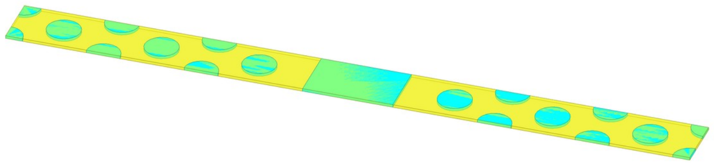


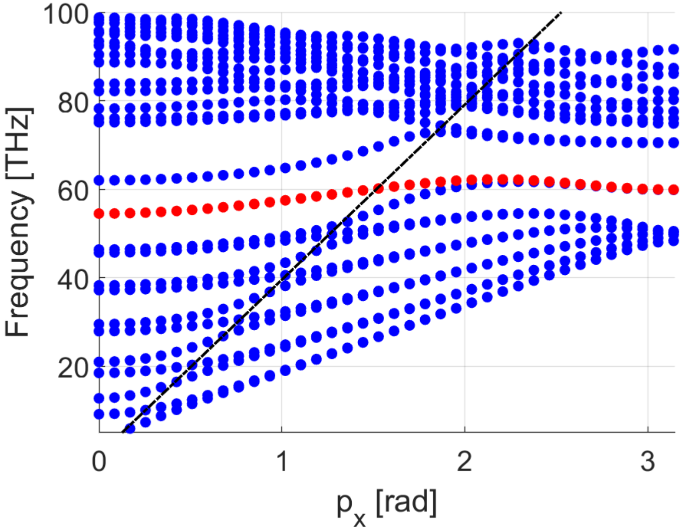
b) computation of the **projected band diagram** of a triangular lattice supercell



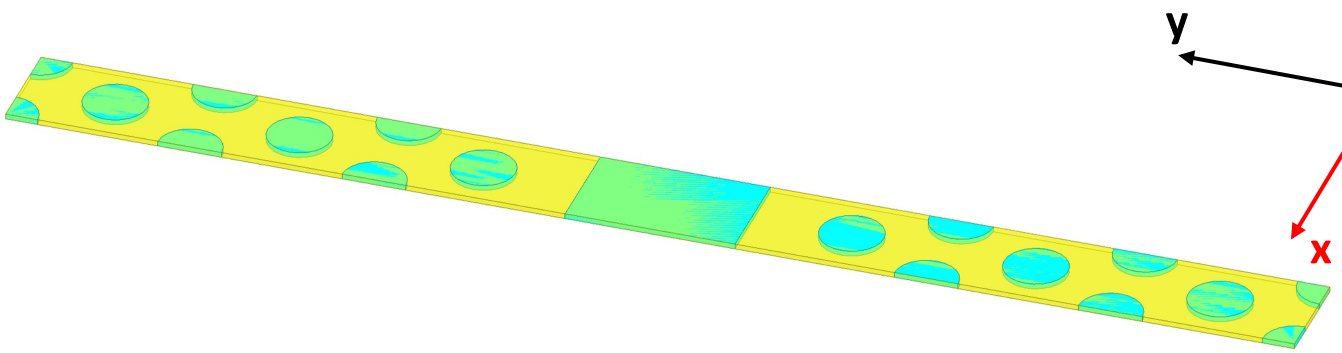


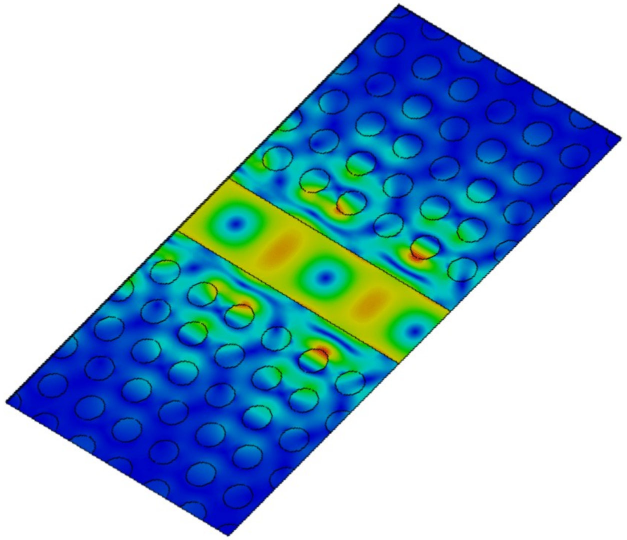
c) add a **hollow-core linear defect** to the supercell



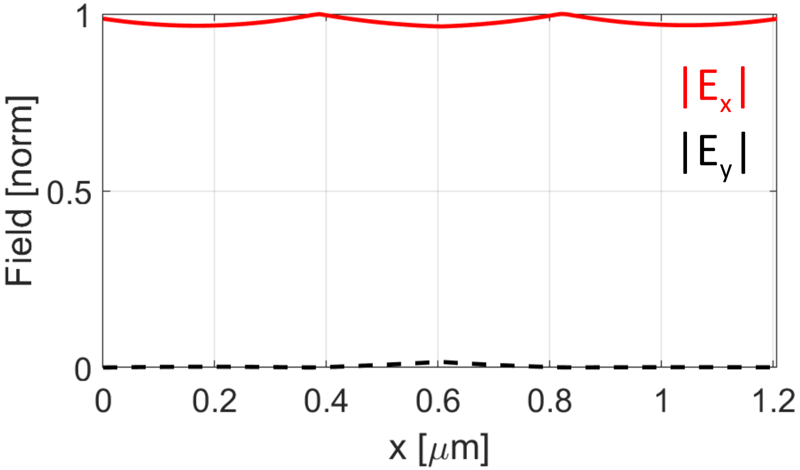


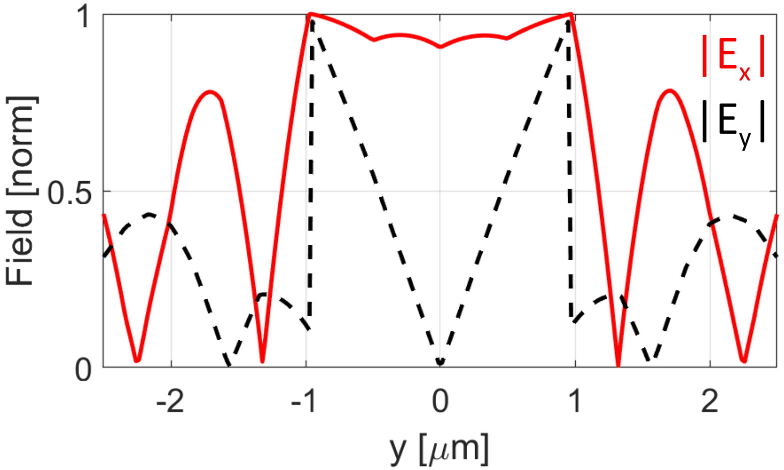
2D photonic crystal waveguide



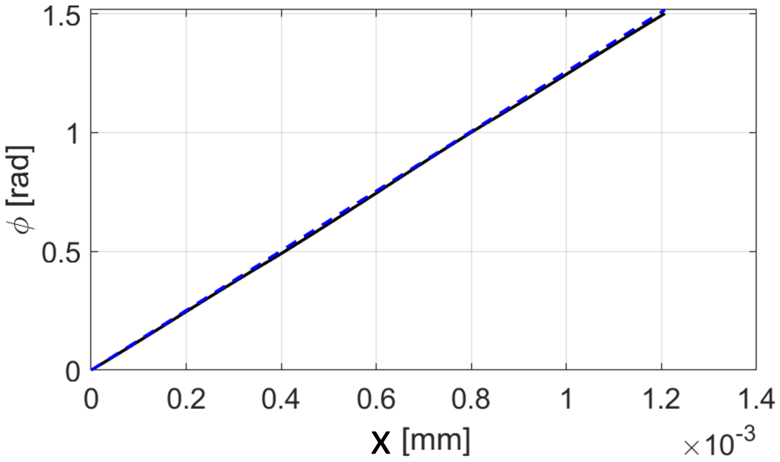


Confined TM01-like mode



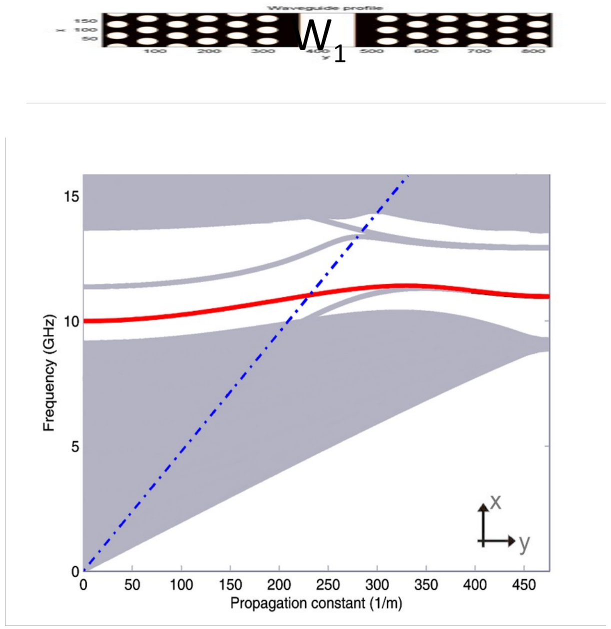


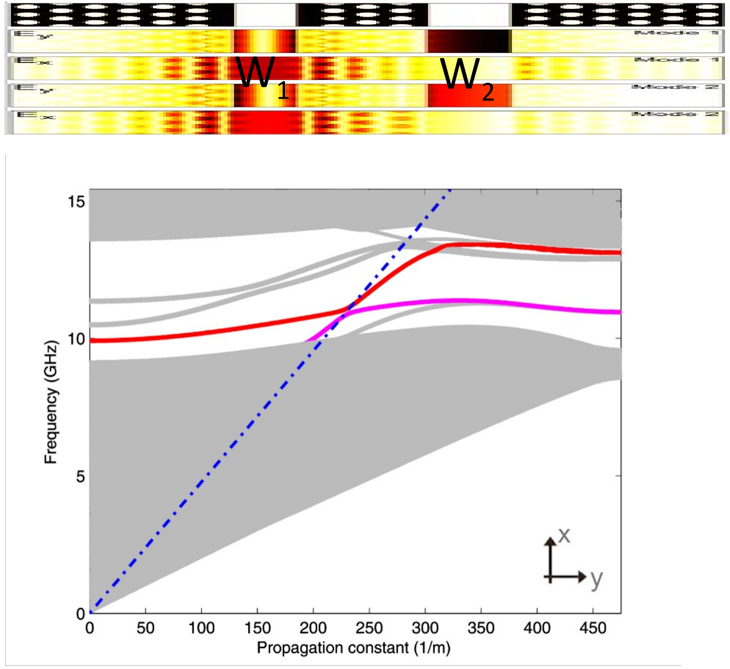
Phase of E_x along x vs.



2D photonic crystal waveguide coupler – first attempt

- The first waveguide (width $W_1 = 1.6d$) supports an **accelerating mode**.
- The second one (width $W_2 = 2.13d$) supports a **transverse mode**.
- Synchronization of an accelerating and a transverse mode by W variation.
- When the waveguides couple, efficient energy exchange is possible.

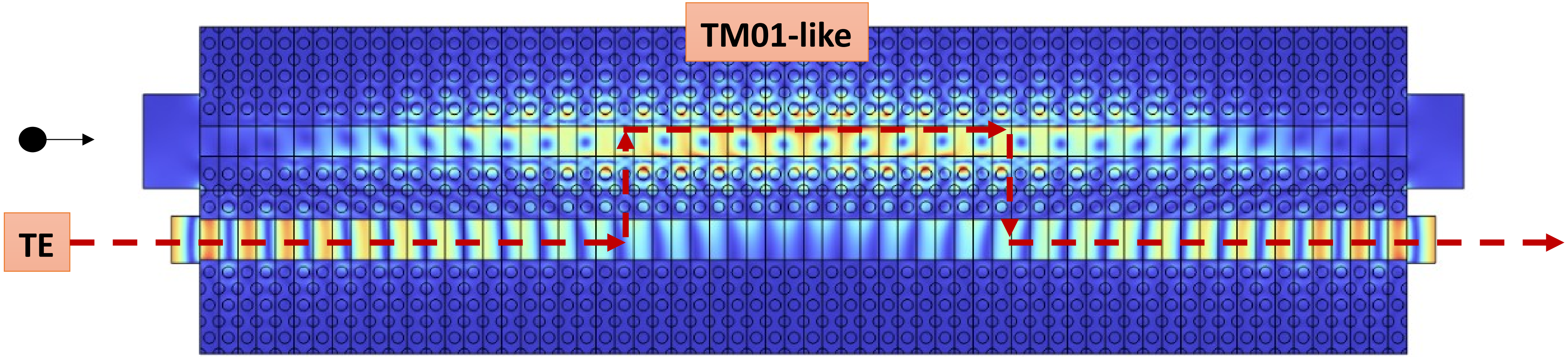




Locatelli et al., «Photonic crystal waveguides for particle acceleration»; 2017

2D photonic crystal waveguide coupler – first attempt

64-periods 2D PhC waveguide coupler COMSOL simulation

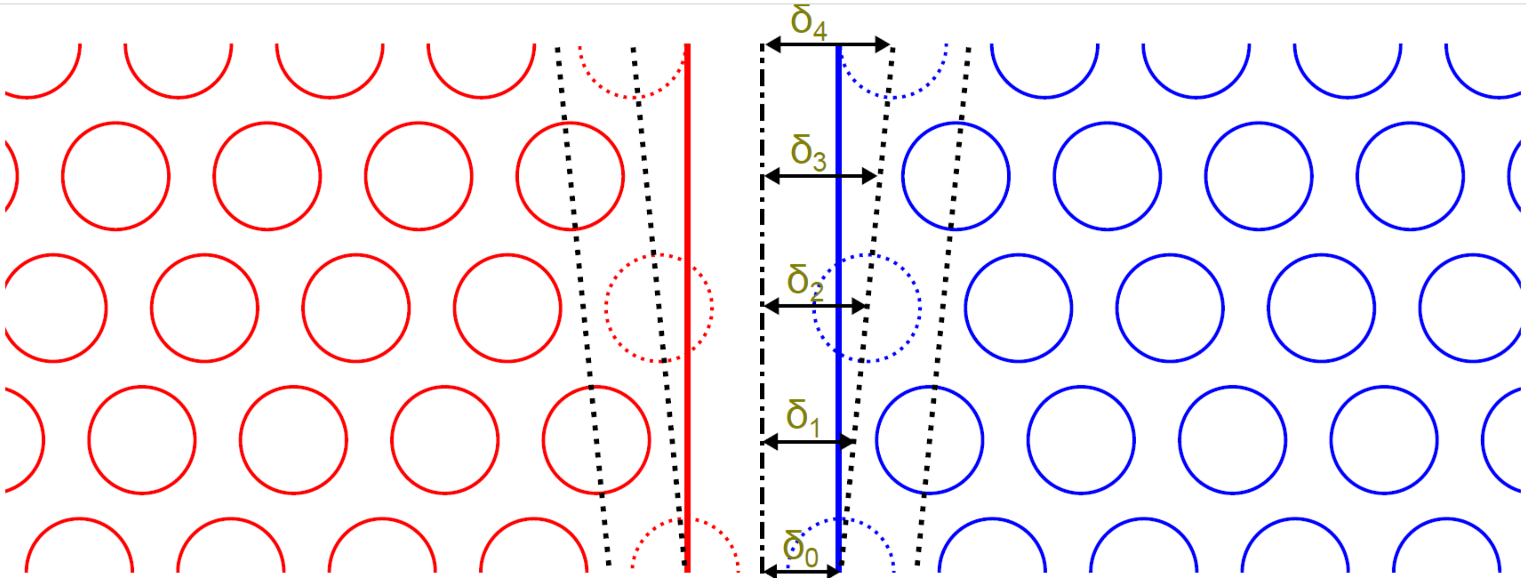


Tapered 2D PhC waveguide

- By modifying the waveguide width, it is possible to decrease the normalized wave phase velocity of the guided mode.

- In particular, the triangular lattice waveguide, we obtain **0.7 < β < 1**.

➢ The decrease in waveguide width necessary to obtain a lower β is accomplished by a shift of the air rods along the transversal direction.



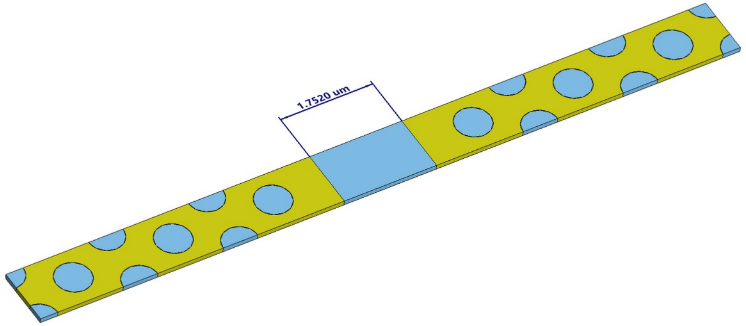
$$\delta_i = \frac{i}{N}\frac{w_p}{2}$$

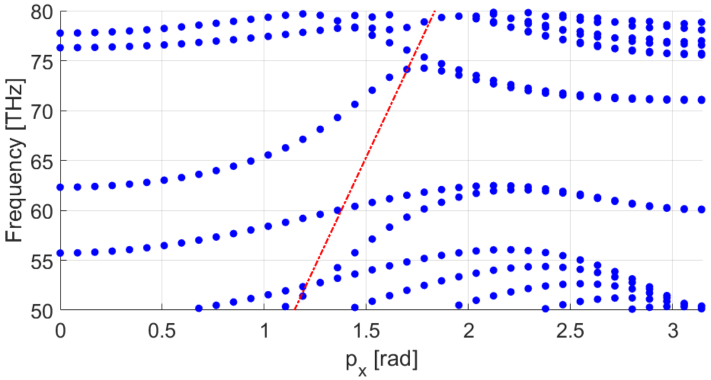
Where:

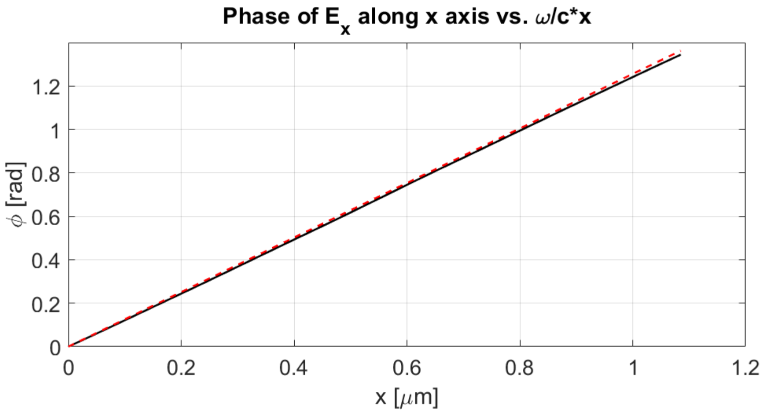
- N is fixed by the taper length
- w_p is the padding width to obtain a specific β

Tapered 2D PhC waveguide

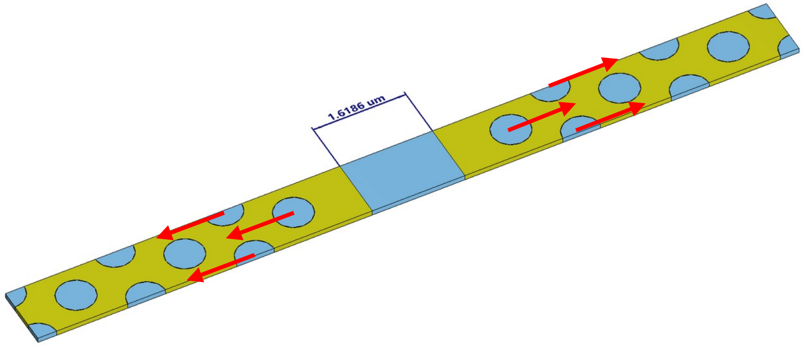
- Phase velocity modification procedure:
- 1 – design a PhC waveguide supercell, choosing the hollow-core defect width in order to obtain a suitable confined mode. In our case, the mode will be **TM01-like with $\beta = 1$ @ $\lambda_0 = 5$ µm**.

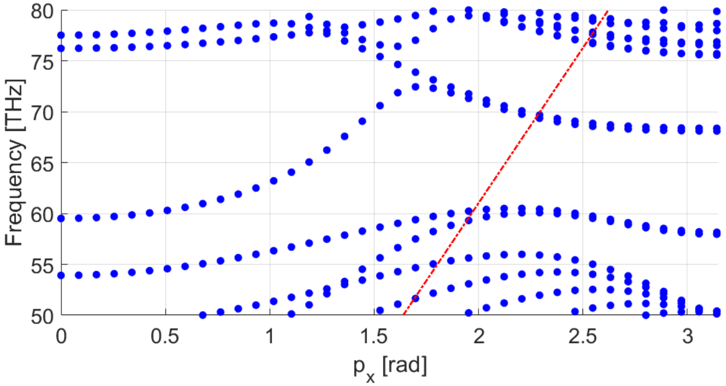


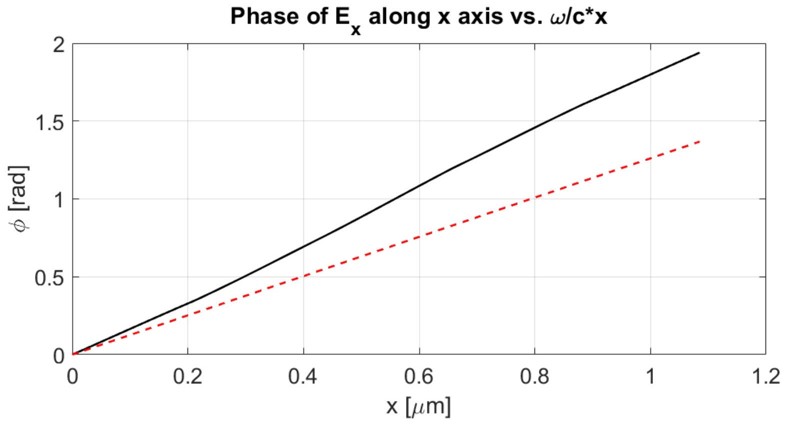




- 2 – introduce a waveguide 'padding' through a suitable air rod side-shift. This way the confined TM01-like mode will intersect the frequency of interest at another value of k_x: here the mode will have **$\beta < 1$.**



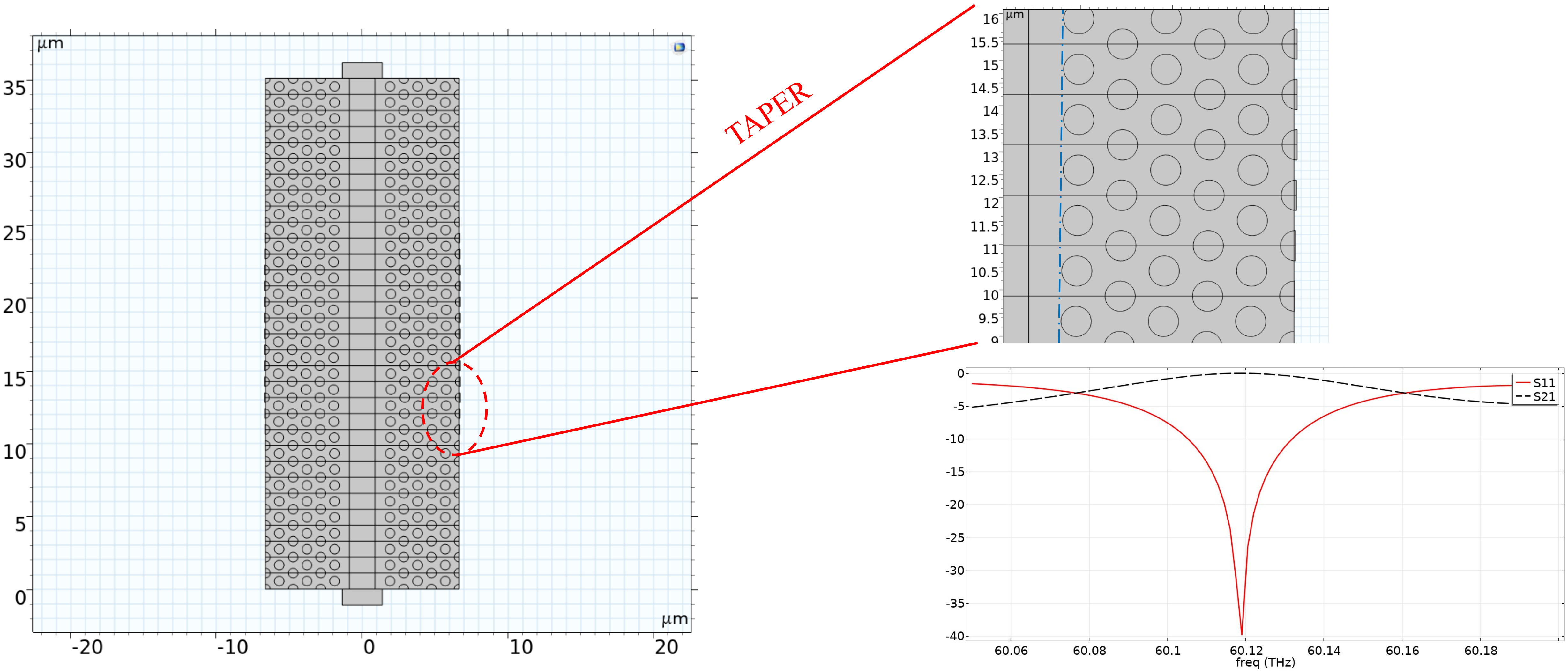




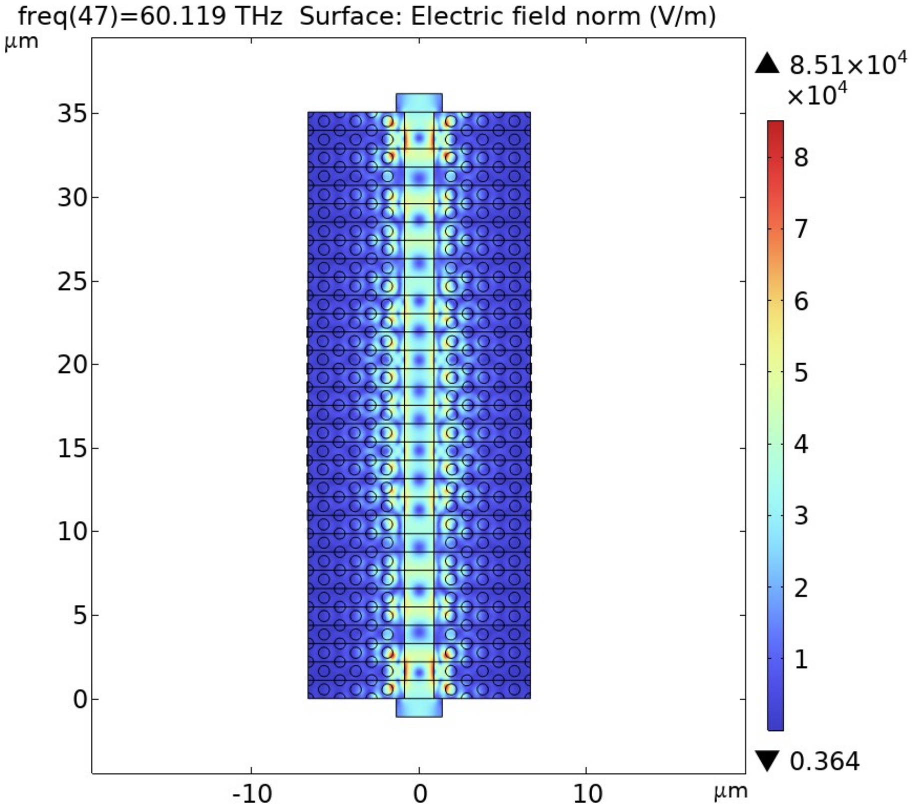
- NOTE: to perform this procedure the chosen mode needs to have the correct slope!

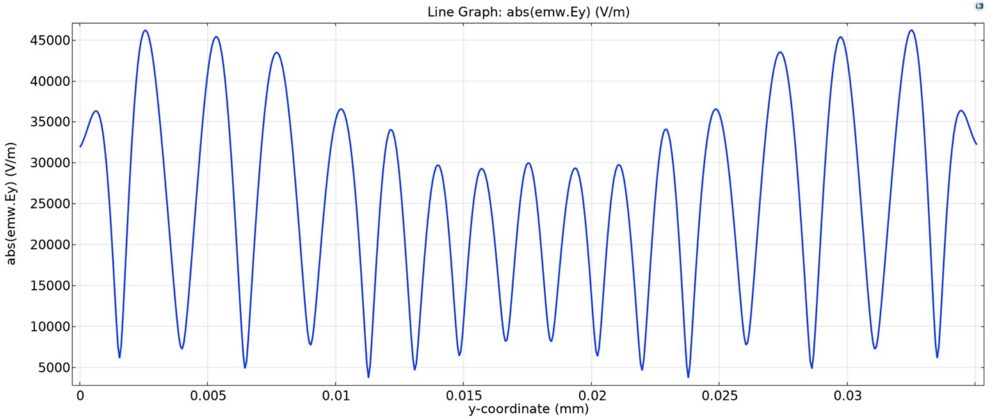
5 µm PhC waveguide in triangular lattice

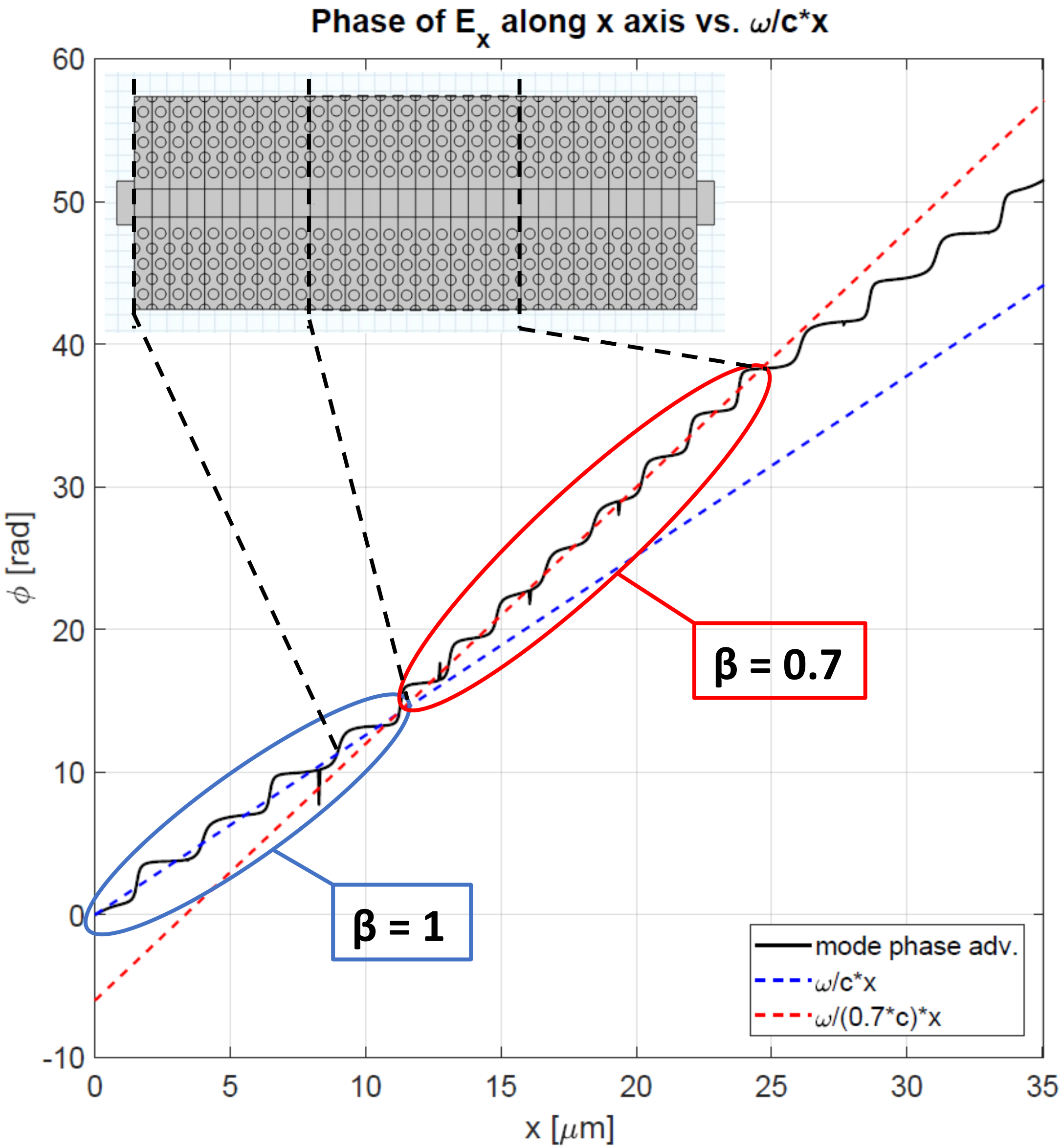
- After the CST periodic boundary condition simulations, necessary to select the accelerating mode (**0.7 < β < 1**), a 2D ‘driven’ COMSOL simulation has been performed.
- Waveguide is made of **32 periods** and works in b2b configuration.



5 µm PhC waveguide in triangular lattice

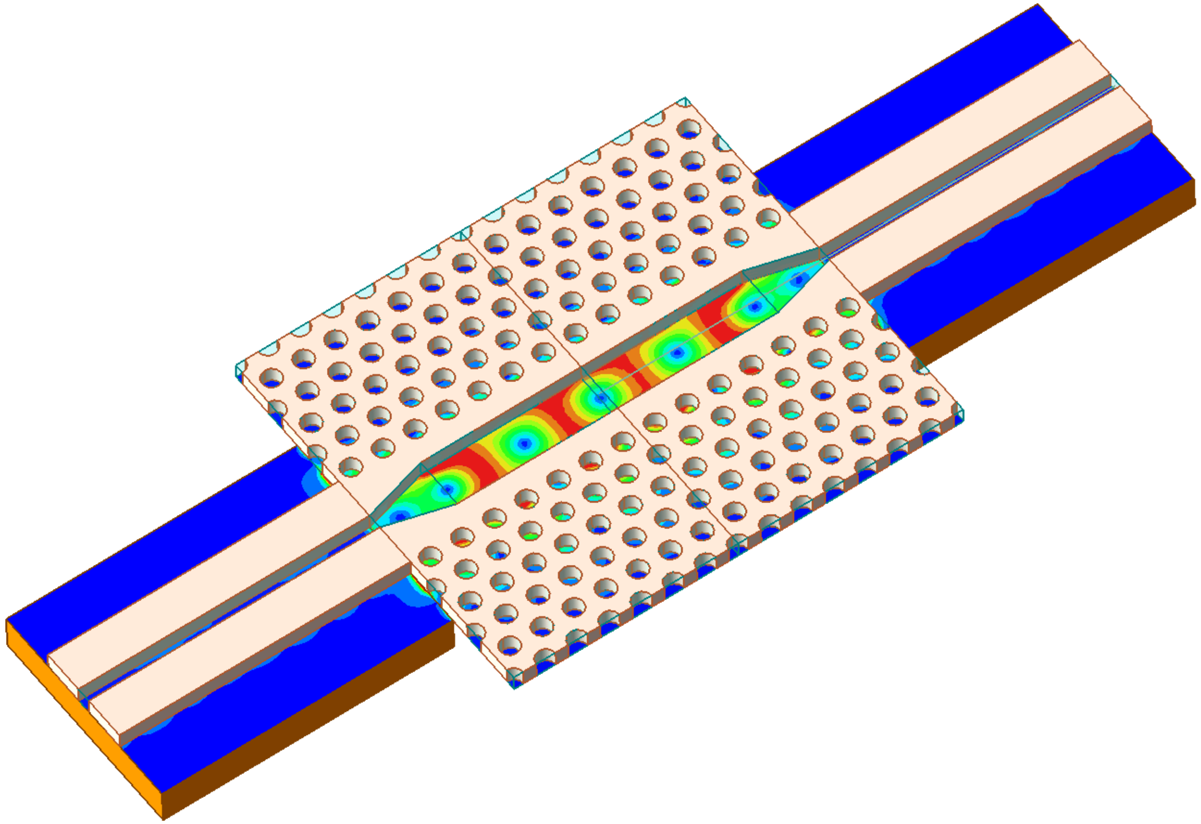


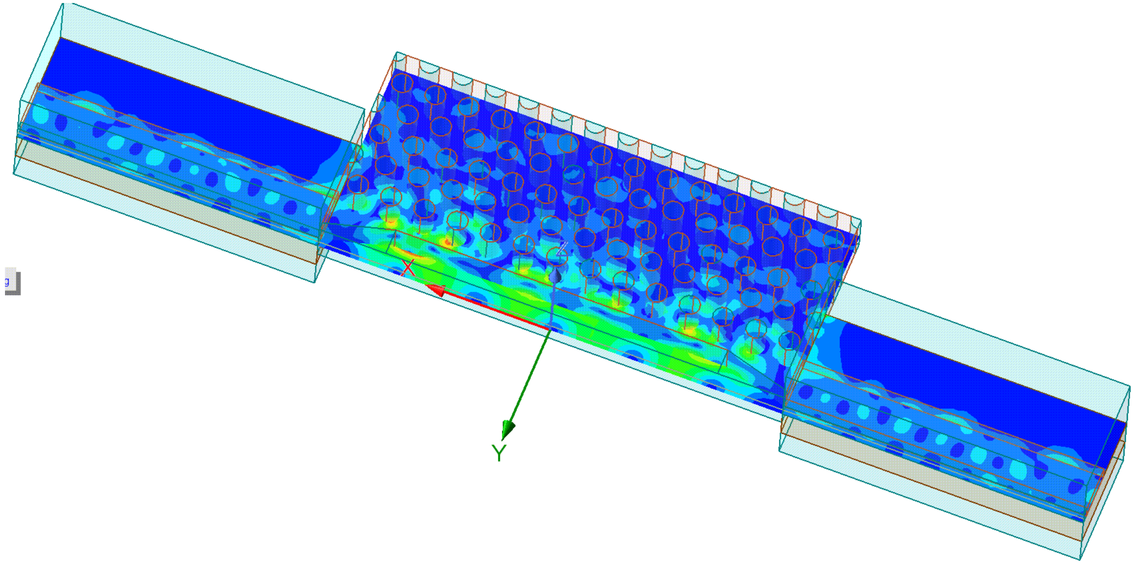




Next steps

➢ Sub-relativistic to relativistic ($0.4 < \beta < 1$) slot waveguide to silicon triangular lattice PhC accelerating waveguide.





Copropagating schemes for Dielectric Laser Accelerators

1) Slotted waveguide @ 2 µm

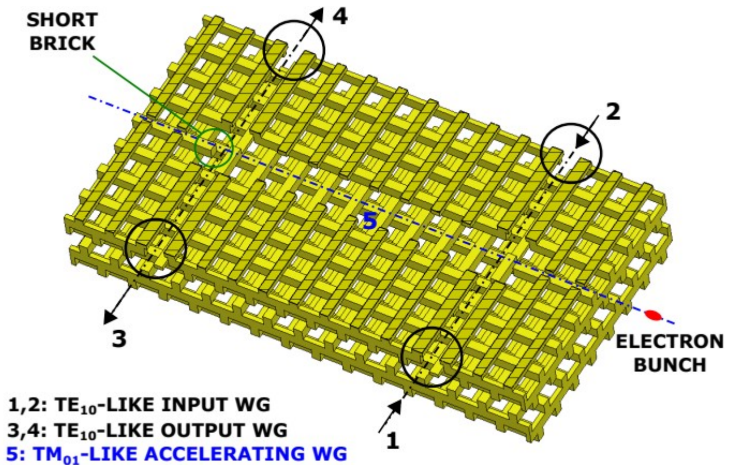
[]

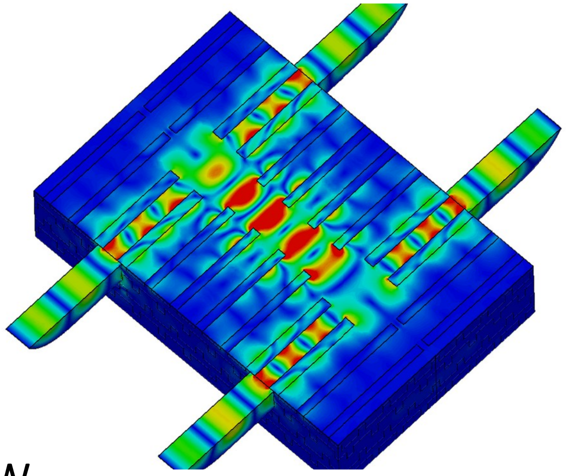
2) 2D PhC waveguide @ 5 µm

[

3) Woodpile @ 5 µm

[]



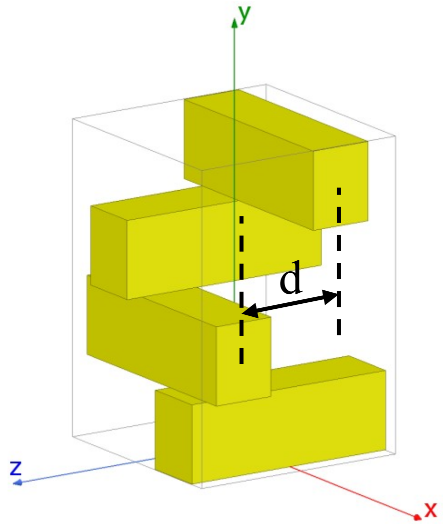


1 GV/m

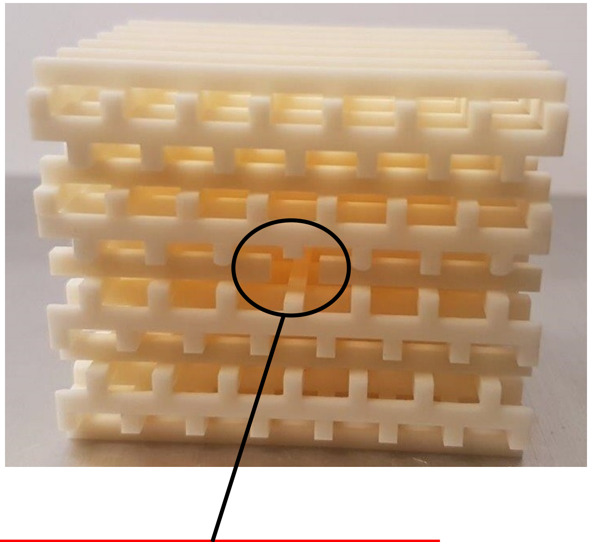
@ P_{INJ} = 500 W

3D woodpile structure

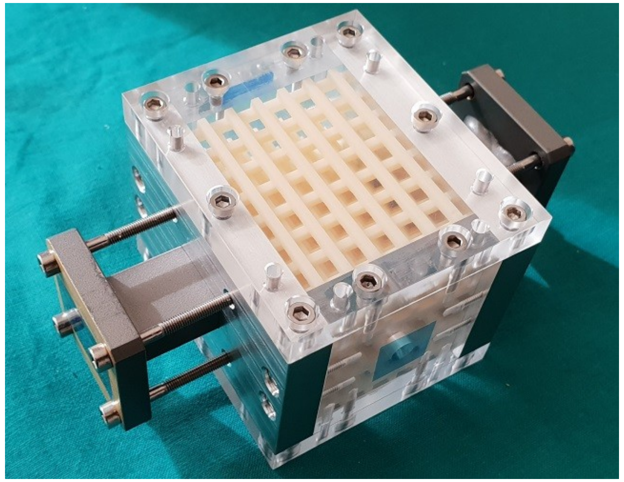
- Composed by a “pile” of rectangular $w \times h$ bricks disposed in layers stacked in the vertical direction, each layer rotated of 90° with respect from the layer below, whose centers are distant a period d.
- Creating a so called “defect channel”, one or more modes can be trapped inside the defect and thus a waveguide is obtained.
- The guided mode can be either a ‘launch’ transverse electric mode (**TE10-like**) or a mode suitable for particle acceleration (**TM01-like**).



Woodpile unit cell



‘Hollow-core’defect channel



Woodpile waveguide

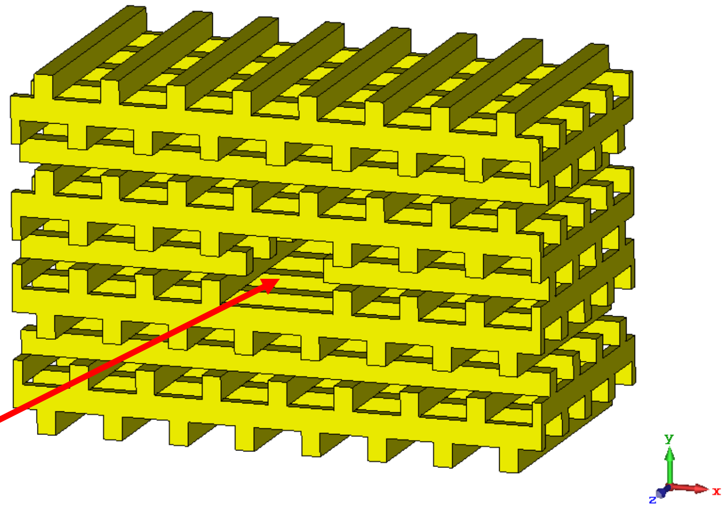
Mauro *et al.*, "Fabrication and Characterization of Woodpile Waveguides for Microwave Injection in Ion Sources," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 5, pp. 1621-1626, May 2020, doi: 10.1109/TMTT.2020.2969395.

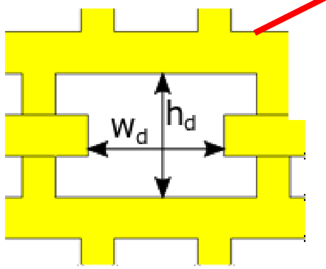
3D woodpile structure

- Once the configuration that presents the largest band gap has been found, a supercell is realized and a hollow core defect is introduced.

- This defect can be tuned to support an electromagnetic mode that can be guided along the structure in the way to form a waveguide.

d = 2.082 μm

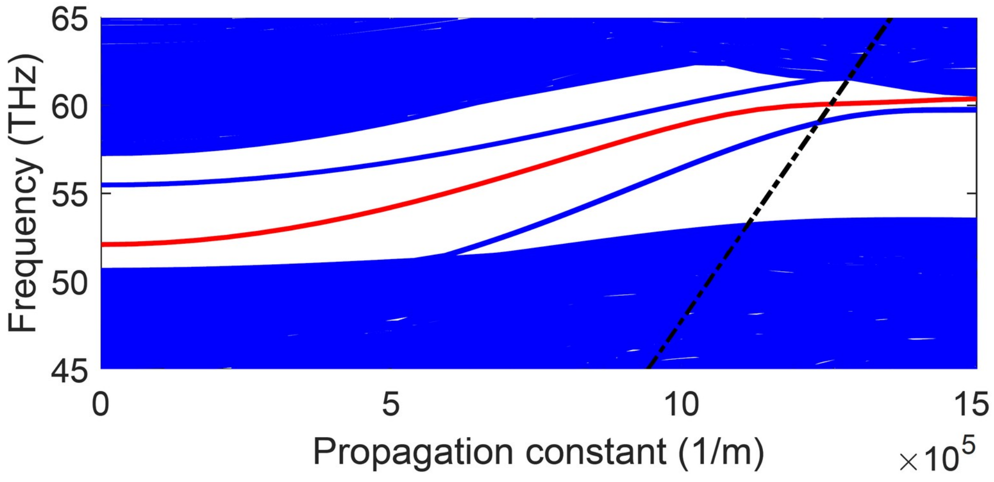




Hollow core defect dimensions:

$\mathbf{w_d}$ = 2.429 μm
$\mathbf{h_d}$ = 2.209 μm

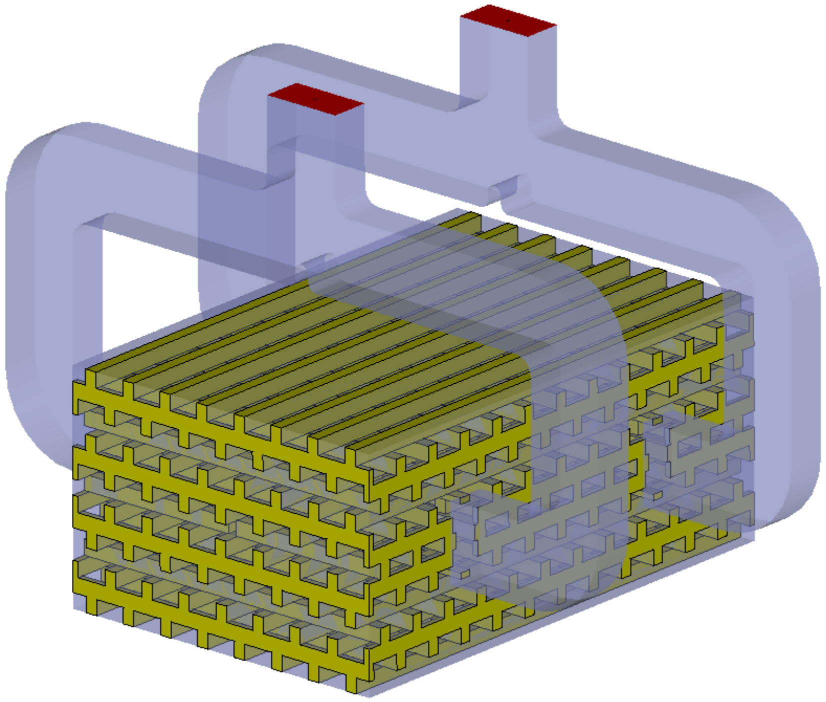
The **length** of the device along the defect direction (z axis) will depends on the desired output energy.



'Projected' band diagram of the accelerating waveguide, calculated along the defect propagating axis (z axis).

The confined TM01-like mode (red line) is clearly visible.

5 μm hollow-core woodpile coupler

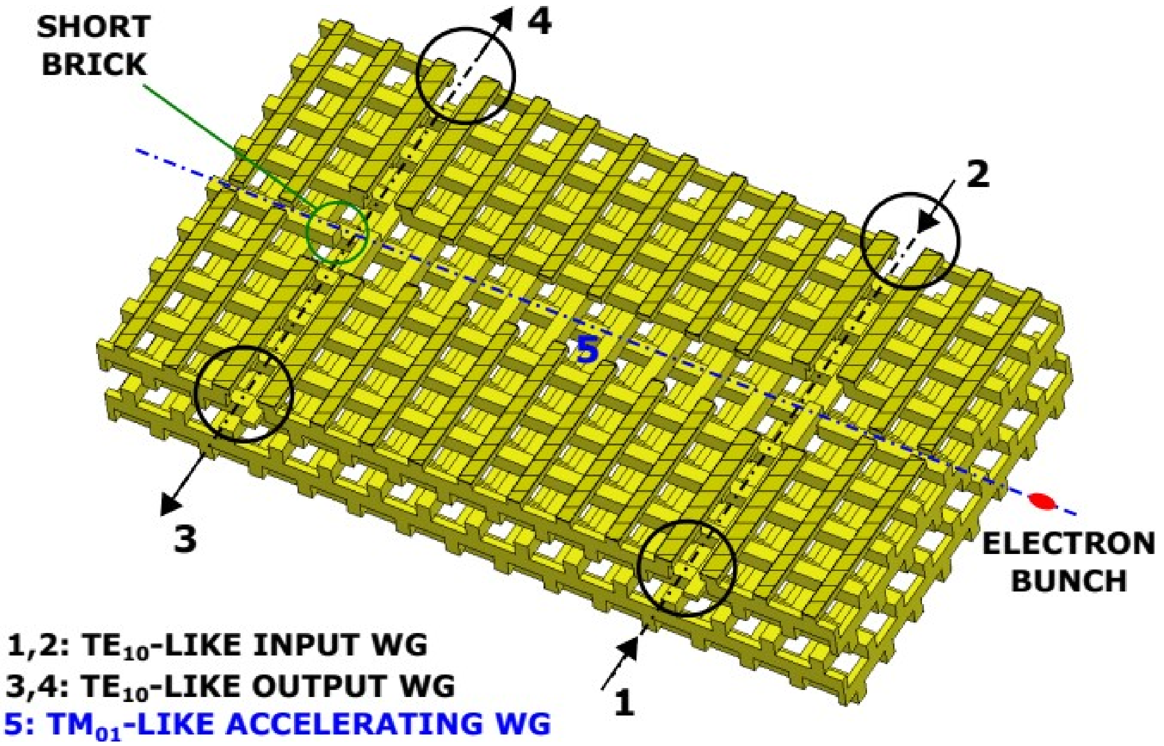


Structure dimensions: **16.7 um x 11 um x 31 um**

- The side-coupler consists of:

1. a **right-angled bend mode converter,** from **TE10-like launch mode** to **TM01-like mode** suitable **for particle acceleration;**

2. an **accelerating waveguide** whose length can be tuned in order to obtain the final energy.



Mauro et al., "Numerical Simulation of a Hollow-Core Woodpile-Based Mode Launcher for Dielectric Laser Accelerators", MDPI Applied Sciences, 2022

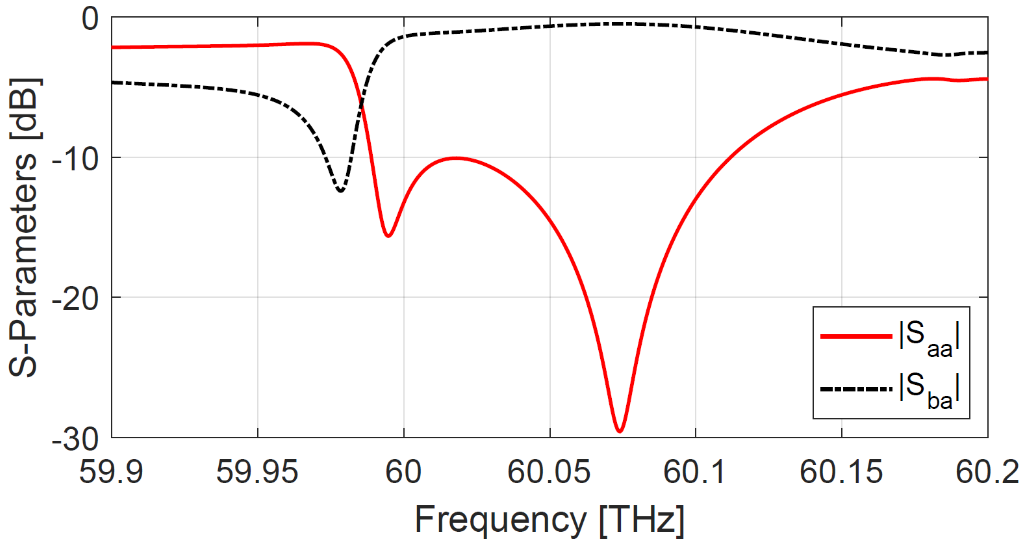
5 μm hollow-core woodpile coupler

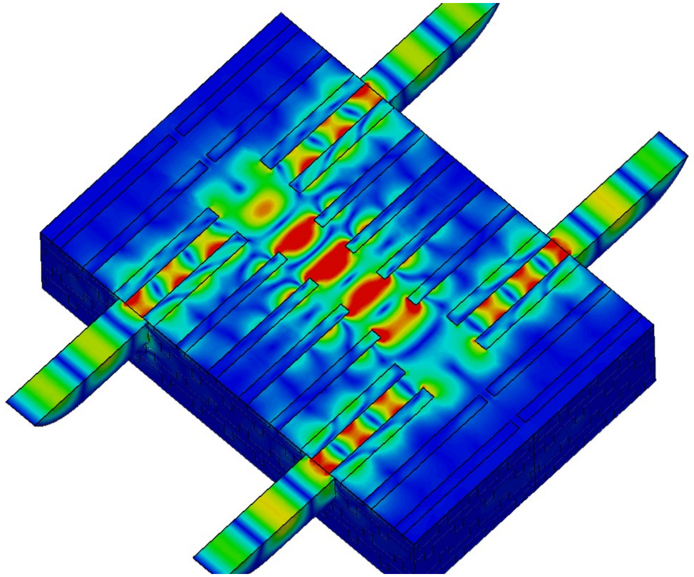
- Woodpile coupler tuned, in terms of S-parameters, to:

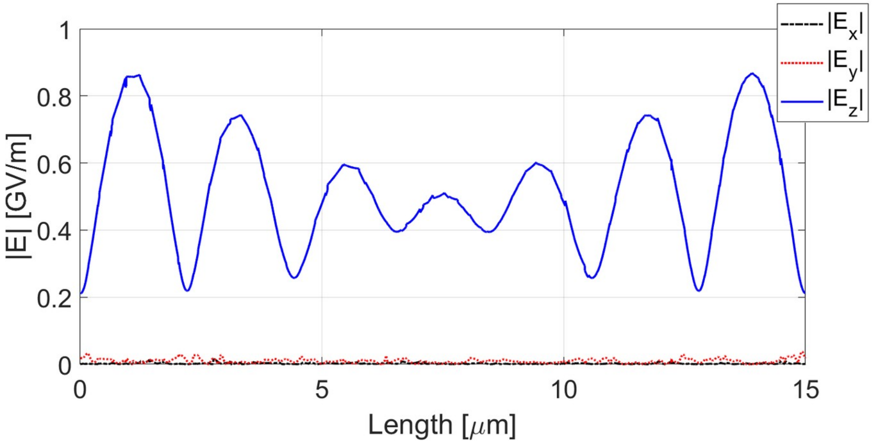
a) maximize the I/O wave transmission;

b) improve the TE10 to TM01-like mode conversion.

- Full mode conversion at $\mathbf{f_0} \approx$ **60.074 THz**.

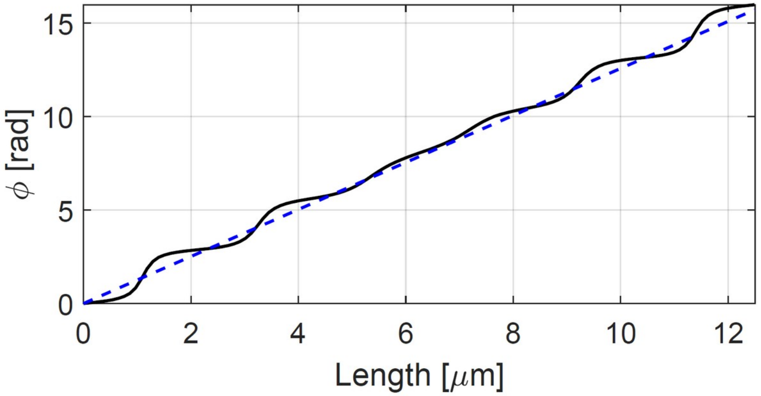






Acc. gradient of about 0.5 GV/m along hollow-core channel with 500 W input power.

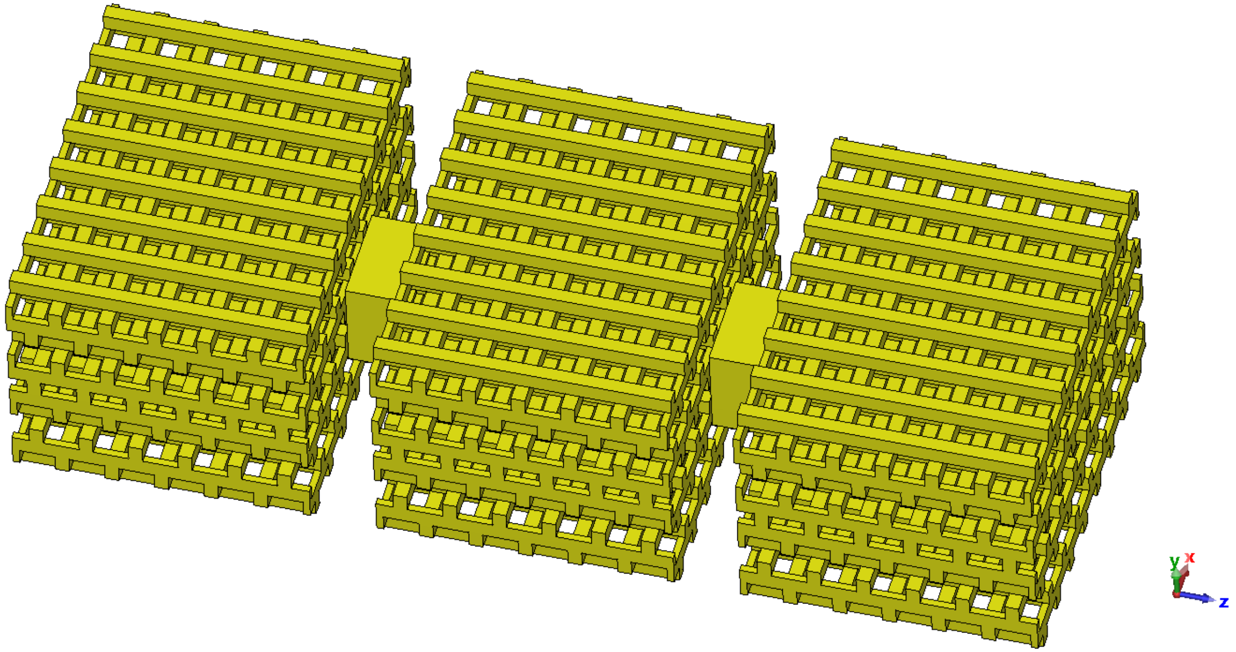
Phase of E_z along z vs.

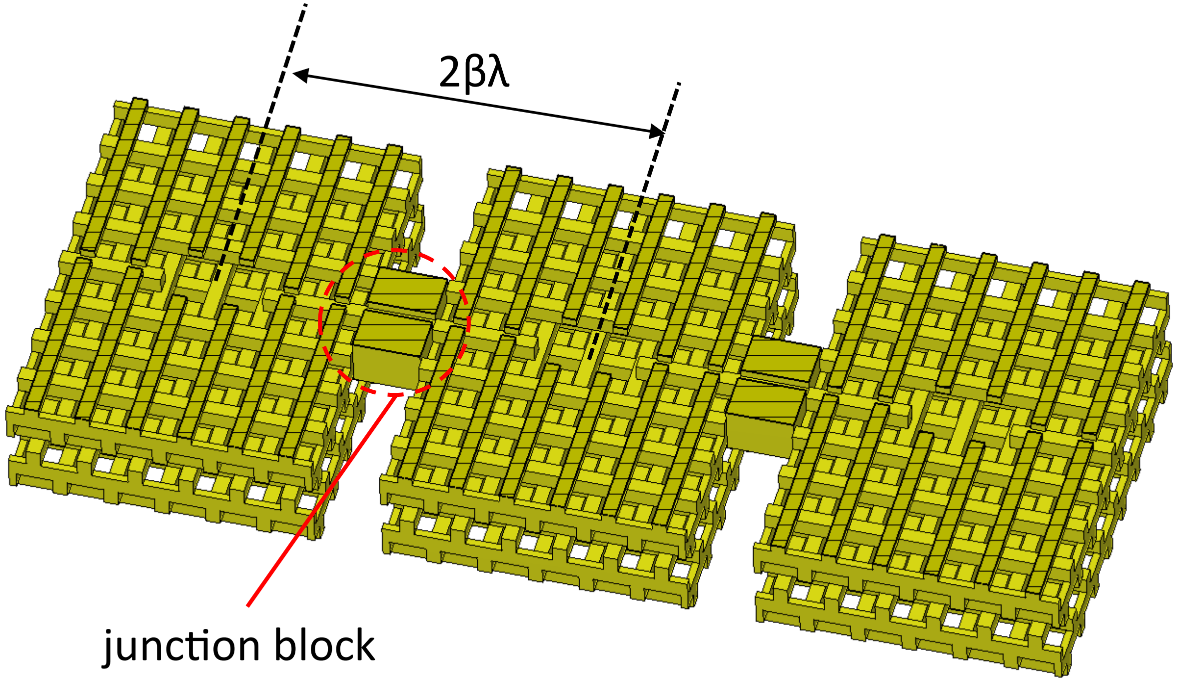


TM01-like mode synchronous with speed of light @ op. frequency.

Woodpile standing wave structures

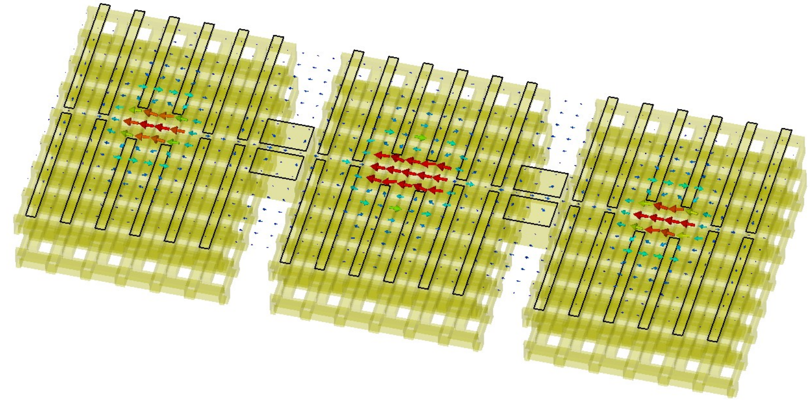
- 3-cell SW structure working in the **TM010-like** mode, $\lambda_0 = 5\ \mu m$.
- From the theory, for 3 cells the TM010-like mode bandwidth comprises 3 modes: 0, π/2, π.



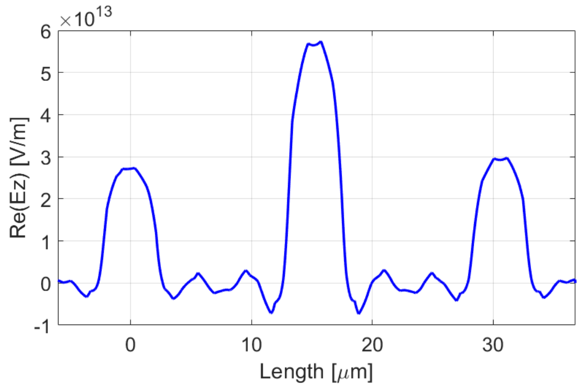


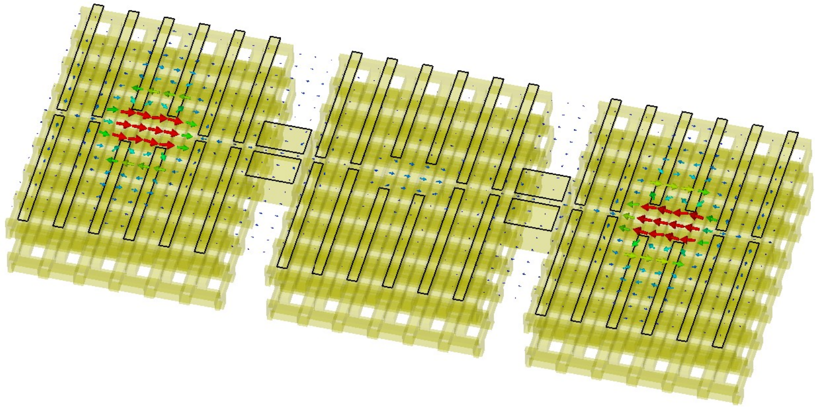
- Distance between two cavity centres is equal to 2βλ (0-mode operation).
- The 3 woodpile cavities are connected by two silicon 'junction blocks' of proper length.
- This design has strong analogies with the equivalent, metallic DTL structures.

Woodpile standing wave structures

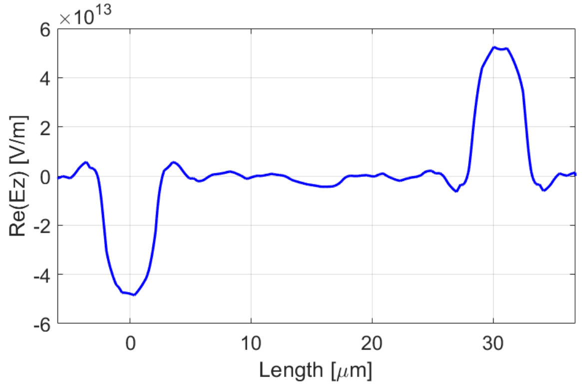


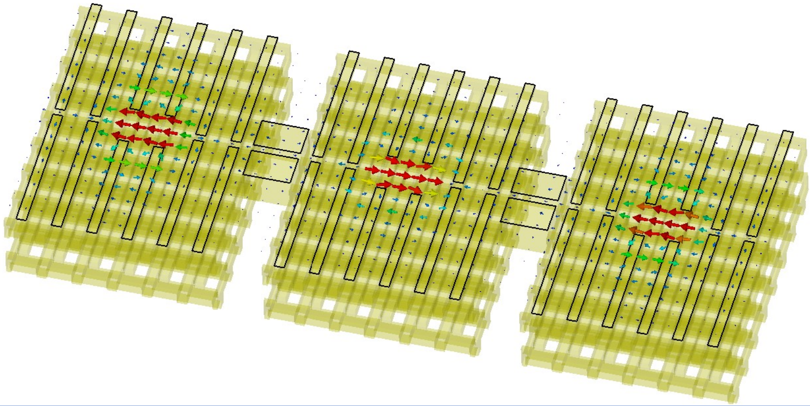
$f_{0\_TM010\text{-}0}$ = 54.18 THz



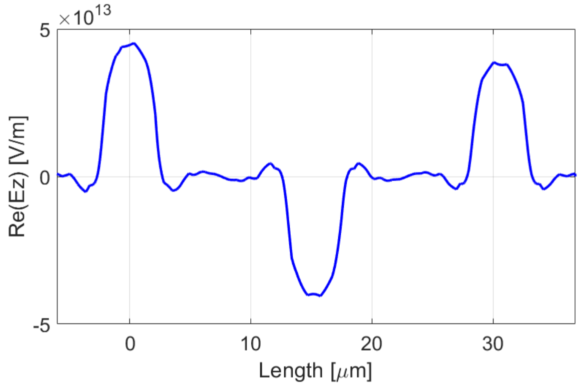


$f_{0\_TM010\text{-}\pi/2}$ = 54.13 THz

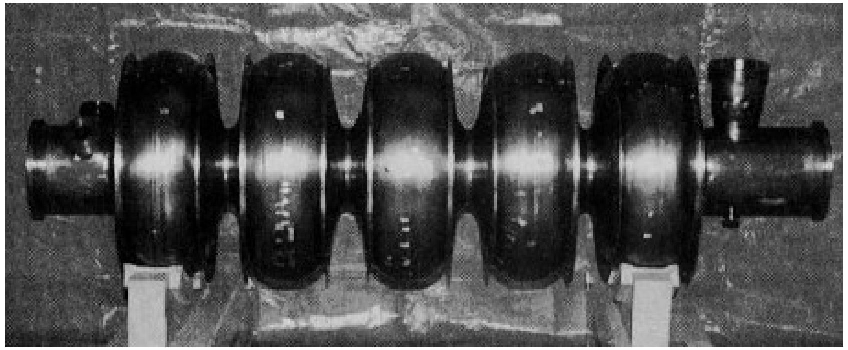


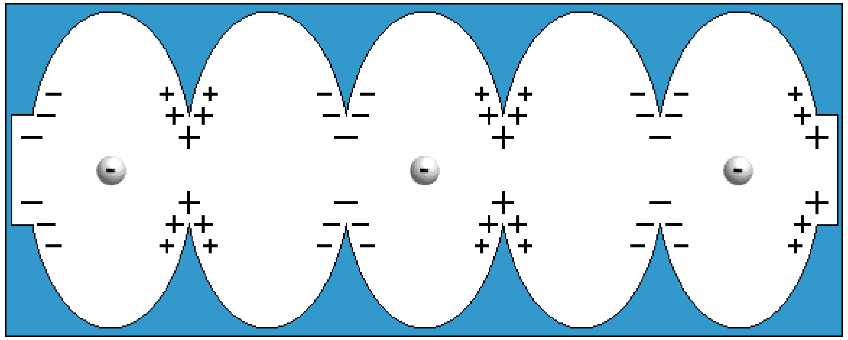


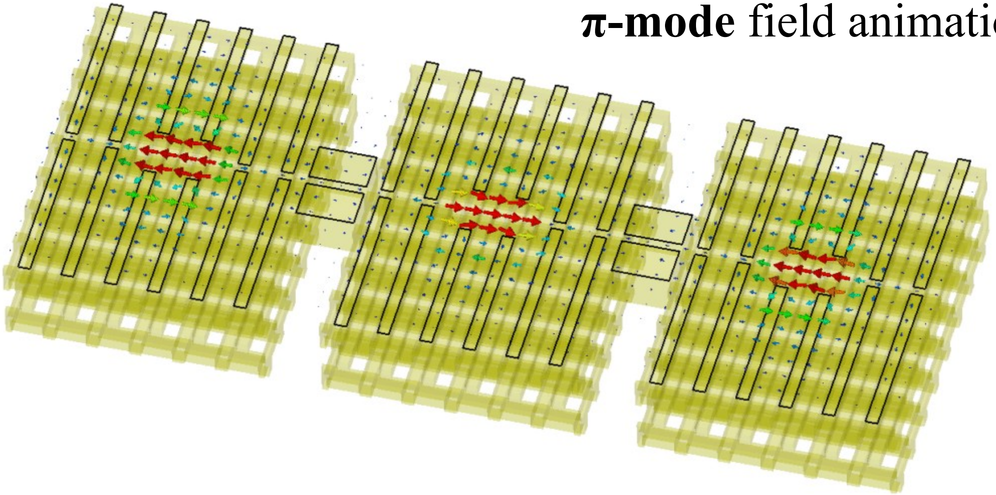
$f_{0\_TM010\text{-}\pi}$ = 54.10 THz



Woodpile standing wave structures







π-mode field animation

➢ **Next step: design of a proper dielectric cavity coupler.**

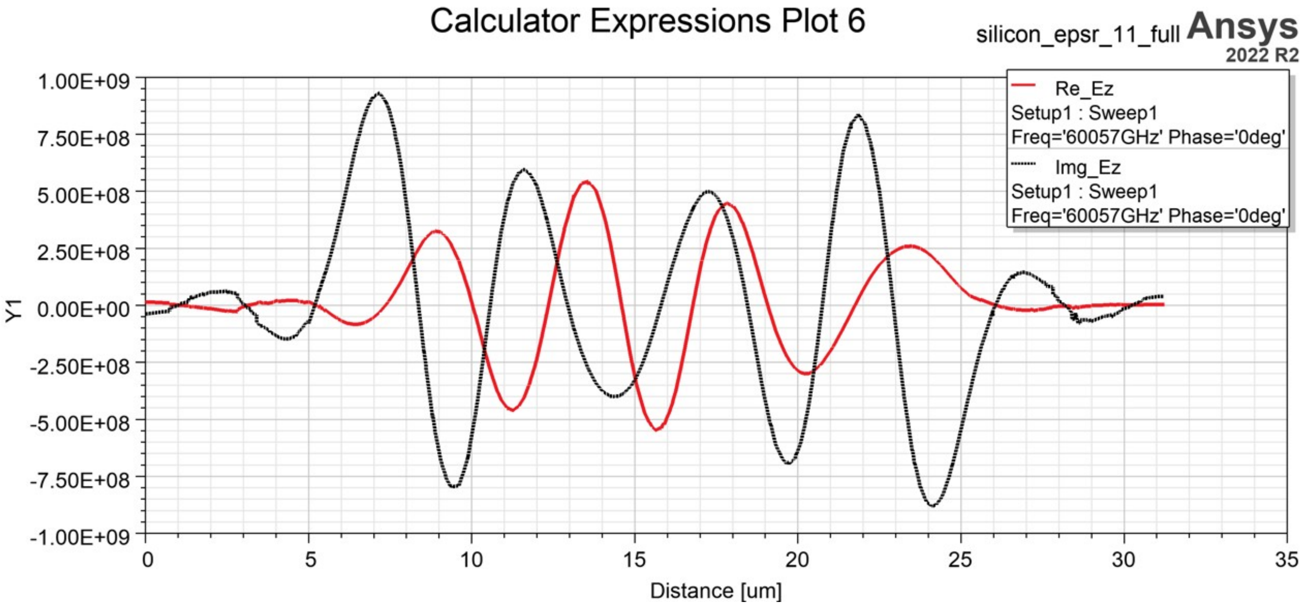
Summary

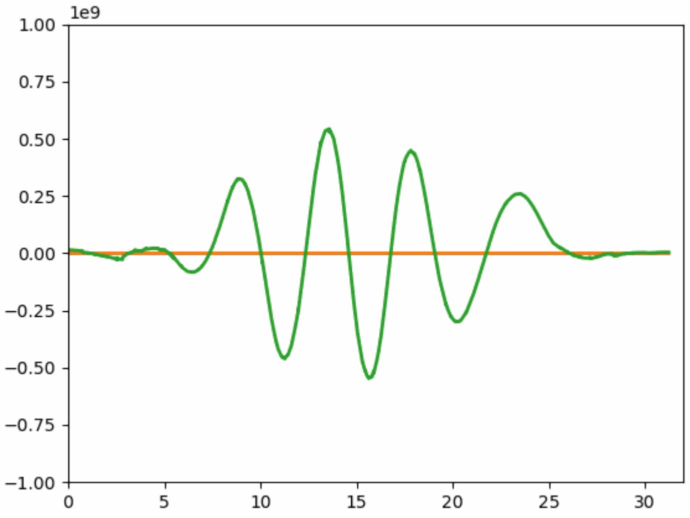
- Dielectric Laser Accelerators: introduction
- Co-propagating dielectric structures
- Beam-dynamics simulation results and fabrication tests
- Conclusion and perspectives

Hollow-core woodpile coupler – Astra BD results

- **September-October 2022**: after various tests, it was possible to correct import and employ a <u>TW</u> in Astra, for BD calculations.

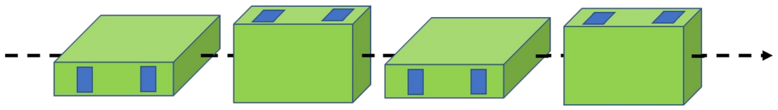
- Astra employs the field calculated and extrated from Ansys HFSS considering a woodpile structure working at **<u>λ = 5 µm</u>** with total length **<u>L = 30 µm</u>**.



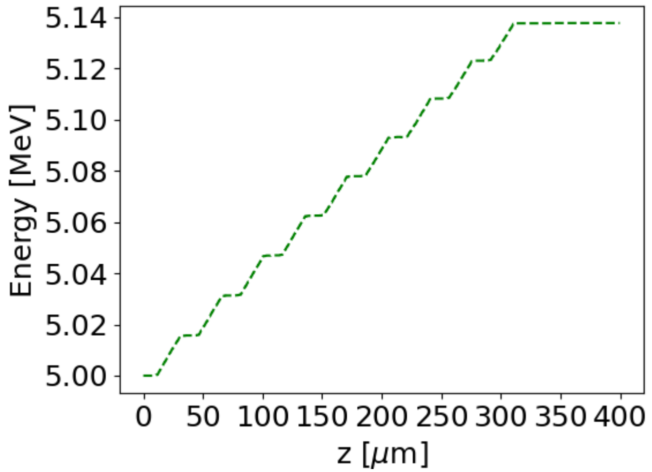


Hollow-core woodpile coupler – Astra BD results

- In order to increase the overall energy gain, a staging of nine L ≃ 30 µm accelerating structures (**λ = 5 µm**) has been considered to perform the simulations over a total length of ≃ 300 µm.



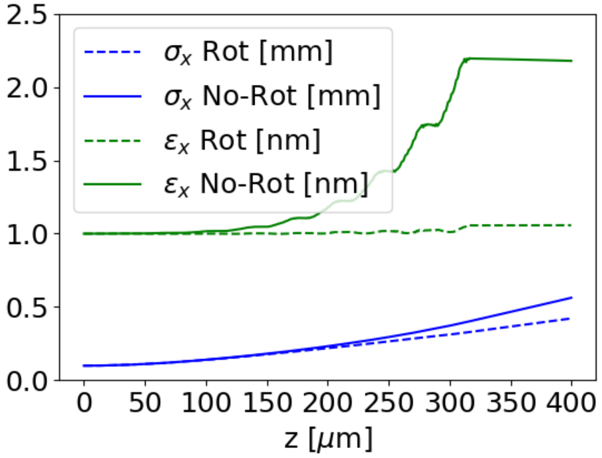
- A bunch charge of 10 fC and a normalized transverse emittance $\epsilon_x = \epsilon_y = 1$ nm have been considered at the entrance of the woodpile stages.



- Considering an input power P_{inj} = 250 W, an energy gain of **140 keV** has been obtained, which corresponds to an average accelerating gradient of ∼ 470 MV/m.

- The guided mode radial field asymmetry, coming from the fact that **the defect is not cylindrical**, has **negative effect on the beam** that, while is not large when considering a single stage, it becomes evident cascading nine structures, resulting in a **strong transverse emittance degradation**.

➢ The effect can be **mitigated by rotating each accelerating ≃ 30 µm long stage of 90-deg relative to each other**. This resulted in a **quasi-perfect preservation of the bunch entrance transverse emittance value**.

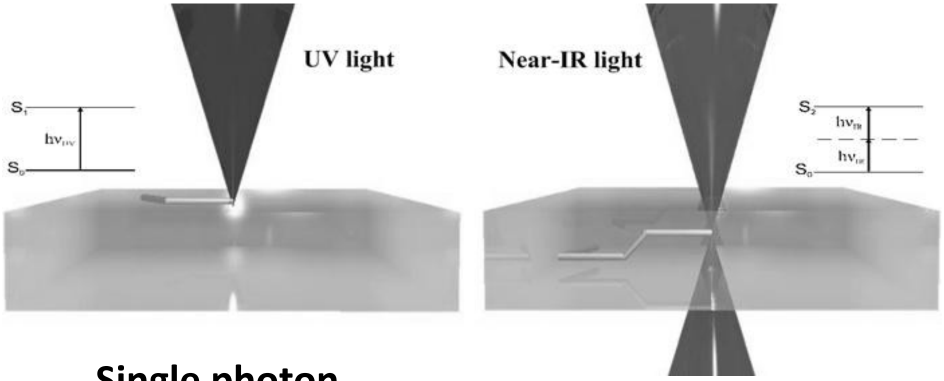


Hollow-core woodpile coupler – fabrication tests

3D printing at the micro/nano scale

Two photo-polymerization (TPP)

Femtosecond pulsed laser to induce resist polymerization



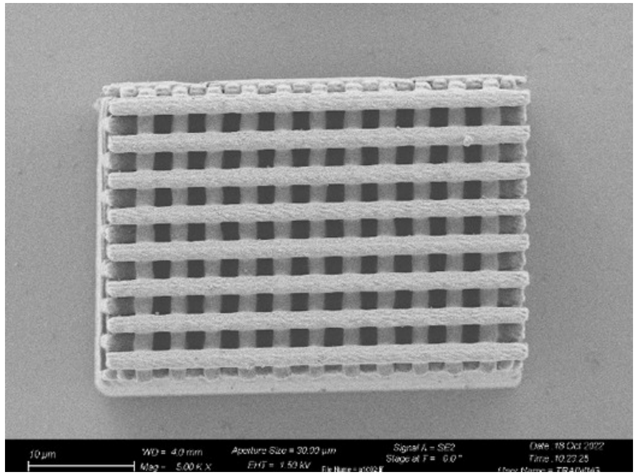
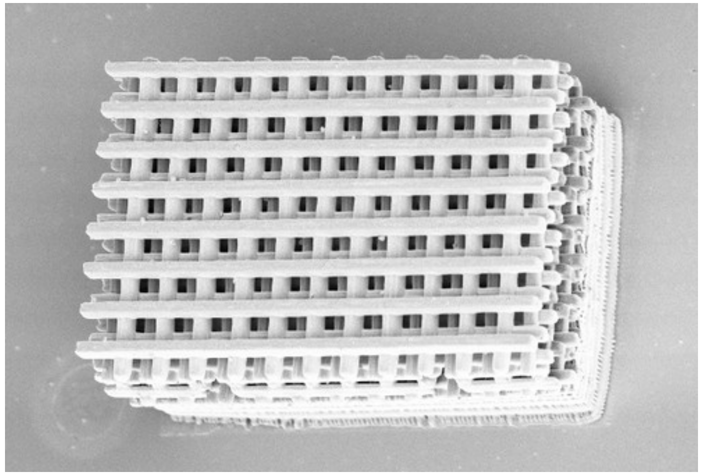
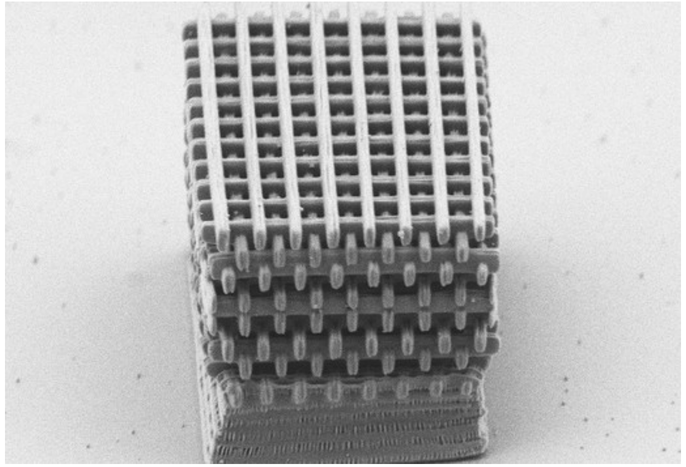
Single photon polymerization (standard): lower resolution, surface polymerization

Two photon polymerization (2PP): higher resolution, polymerization inside volume

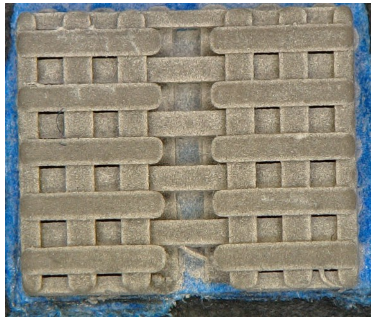
M4D System by Laser nanoFab
TPP setup

Hollow-core woodpile coupler – fabrication tests

- **March 2024: latest results <u>(woodpile @ λ = 5 um)</u>**
- Employed material: FemtoBond resin.

➢ **Future work: print a <u>λ = 3.3 mm structure</u>** with a lab-made resin possessing alumina-like electrical characteristics.



➢ **Characterization of the λ = 3.3 mm** structure with standard laboratory equipment:

1. Measurement of S-parameters with W-band VNA;
2. Measurement of the on-axis alectric field through the bead-pull technique.

Funding and resources

INTERNAL

- INFN Project MIniaturised aCceleRatOrs Network (MICRON) (2022-2024) [˜300 k€]

µICRON
MIniaturised aCceleRatOrs Network

EXTERNAL

- Italian Project PRIN DOSE (Dielectric Optical acceleratorS for hEalth) (2024-2025) [~ 232 k€]
- Italian Project PRIN IDEAS (Inverse Design of tErahertz interAction Structures) (2024-2025) [~150 k€]
- PNRR SAMOTHRACE (2023-2025) [150 k€]
- EIC Pathfinder MODAL [~3 M€] *submitted*

THESIS

- Master Thesis DFA-UniCT: “Modelling of Tapered Co-propagating Structures for Dielectric Laser-driven Accelerators” (DLA) A. Leiva Genre;
- “Numerical study of transverse beam dynamics for non-relativistic electrons in Dielectric Laser Accelerators”, S. Quevedo *on going*
- *UniCT Master Thesis, Marta Maria Costanza*

Summary

- Dielectric Laser Accelerators: introduction
- Co-propagating dielectric structures
- Beam-dynamics simulation results and fabrication tests
- Conclusion and perspectives

Conclusion and perspectives

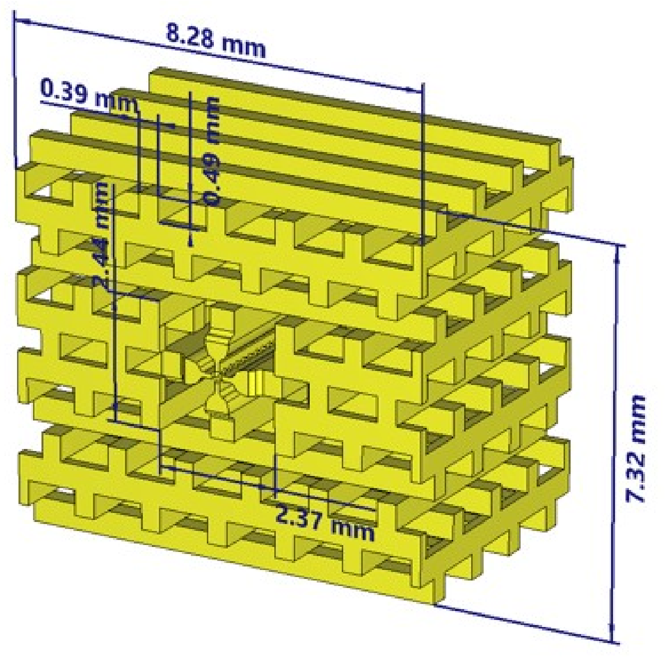
- The design of compact dielectric structures, based on PhCs, for future DLAs setups, has been presented.
- These devices allow co-propagation of the acceleranting wave and the beam.
- Improvements: energy gain efficiency and structure compactness.
- **MICRON** (**MI**niaturised a**C**cele**R**at**O**rs **N**etwork): INFN 5th Nat. Committee project. Ongoing.

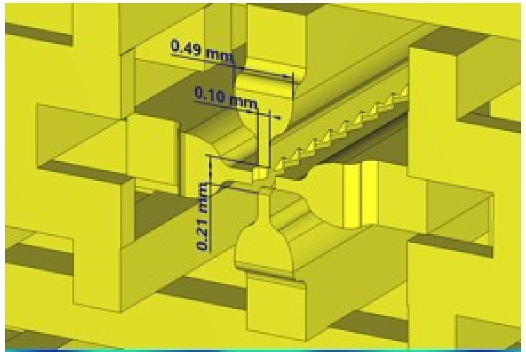
➢ **Next step: woodpile 3.3 mm prototype realization and characterization.**

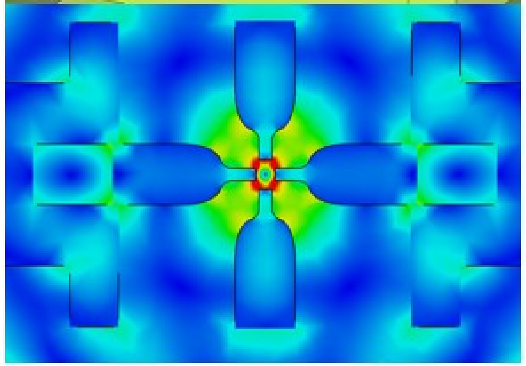
➢ **Next step: numerical study of a sub-relativistic to relativistic structure (slotted wg + PhC wg).**

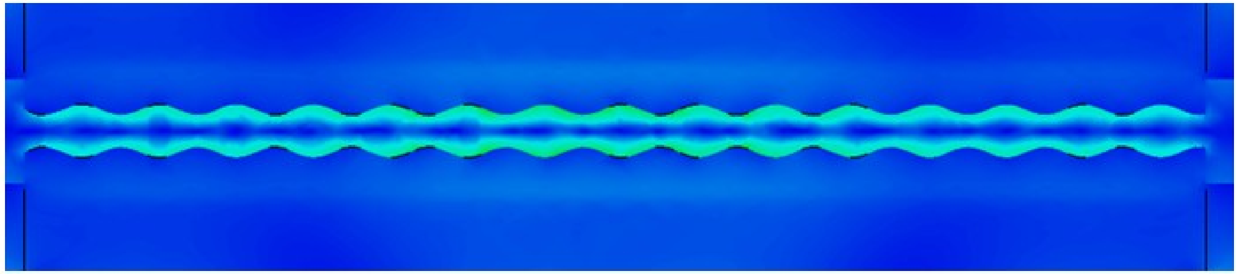
Preliminary design of very low β structures

- **Preliminary numerical study of DLA structures for low- (0.05 to 0.2) particle acceleration (protons).**









Patent
Metodo per progettare una struttura accelerante dielettrica che supporta un modo TE_{210}-like perturbato
(Ita. Patent pending n. 102021000021158)

By: G. S. Mauro, G. Torrisi, D. Mascali, G. Sorbello, S. Gammino (INFN-LNS), G. Della Valle (PoliMi)

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

μICRON
MIniaturised aCceleRatOrs Network

Electromagnetic design of novel synchronous waveguides for Dielectric Laser Accelerators

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A. Bacci, **A. Locatelli**, *INFN-Milano, UniBS*
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Thank You!

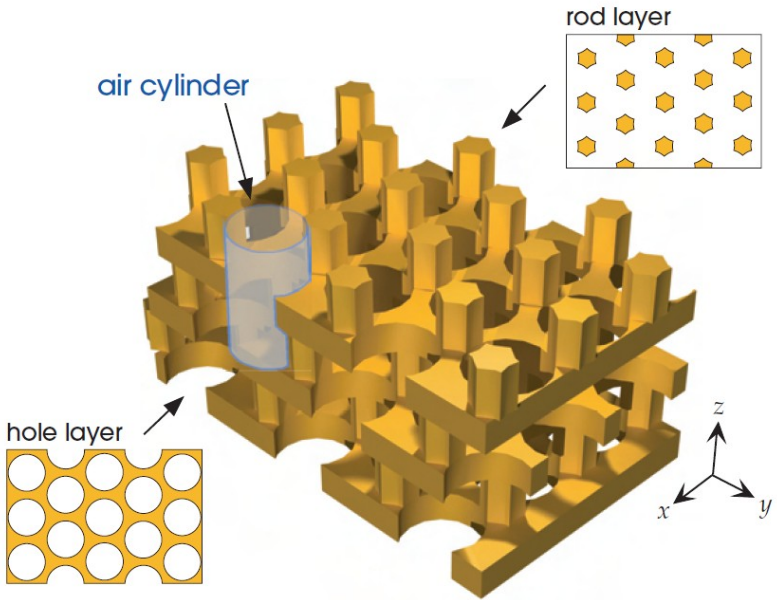
Backup

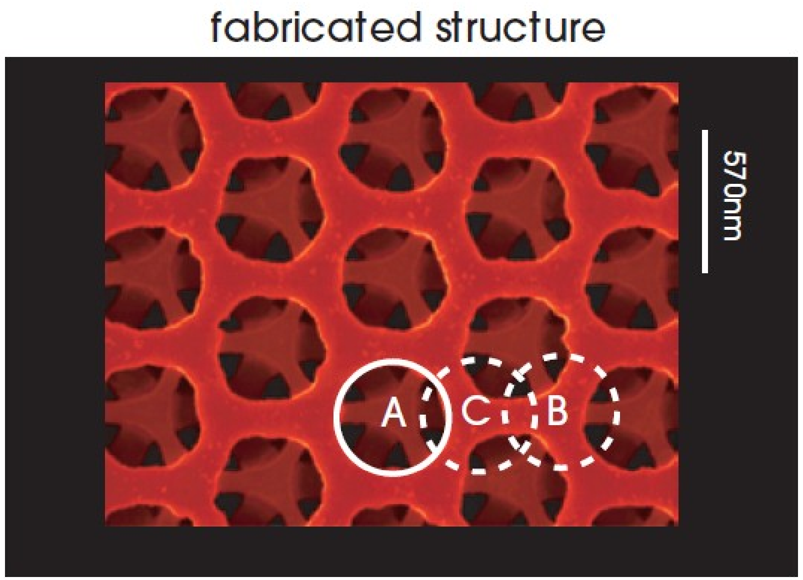
Issues and next steps

- Current issue being investigated: E-field of the confined mode presents some stationariety when passing from CST PBC Eigenmode simulation to ‘driven’ COMSOL simulation.
- This may be due to incorrect COMSOL BCs…

- **Future work:**

1. try to realize a full-3D design of the PhC waveguide in triangular lattice;
2. Selection of the proper vertical ‘enclosure’.





3D woodpile structure

- The **periodic structure** repeats in the stacking direction each four layers, creating a **frequency band-gap** where the EM propagation is suppressed.

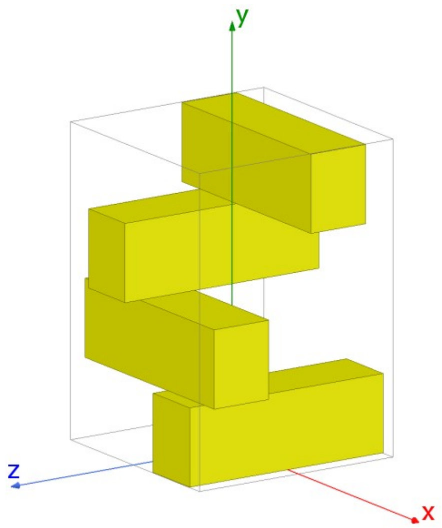
- The band-gap can be calculated using the MIT Photonic Bands (MPB) tool considering an **unit cell with periodic boundary conditions**.

- Design procedure carried out using **normalized frequency and normalized dimensions**.

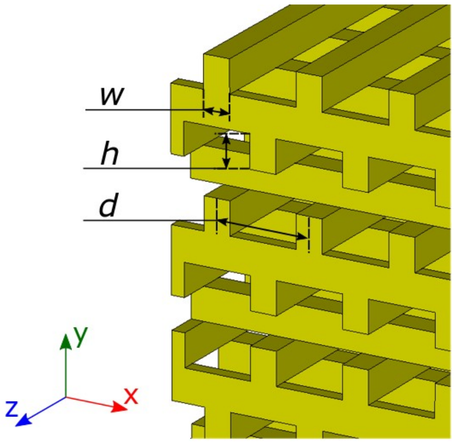
- Once the fundamental (normalized) parameters have been obtained, the structure can be scaled at the **final operating frequency**.

- By setting the period ***d*** the operating frequency can be selected : in order to operate at f_c **= 60 THz**, we choose d **= 2.082 µm**.

$$f_c\,(\mathrm{THz}) \approx f_{norm} \times c/d$$



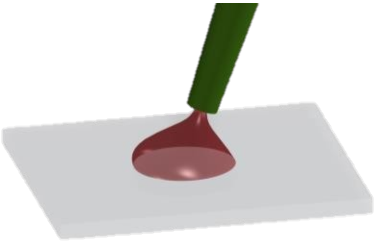
Woodpile unit cell



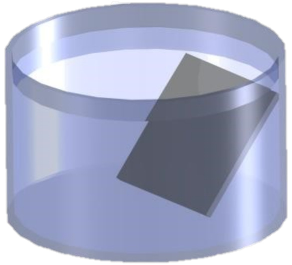
width (**w**) = 588 nm

height (**h**) = 736 nm

Hollow-core woodpile coupler – fabrication tests



2PP direct writing, which polymerizes the resin through a fs-laser

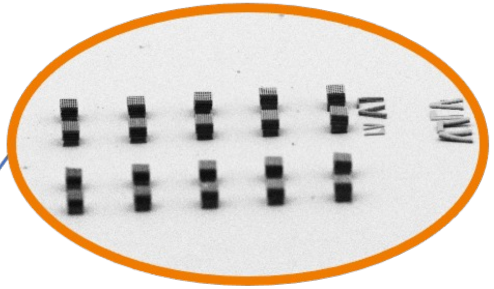


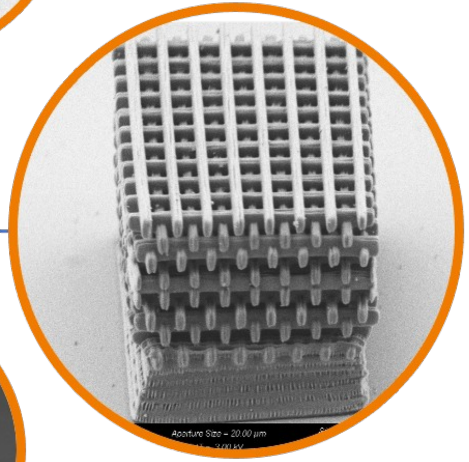
Sample preparation by drop-casting characterized by solvent evaporation

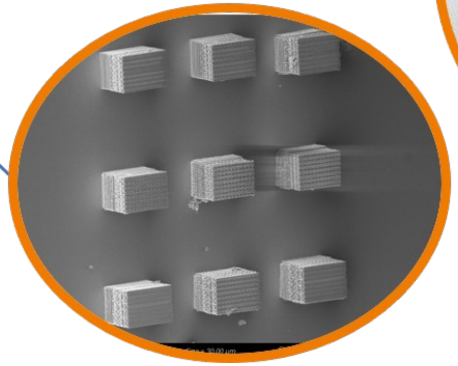
Development

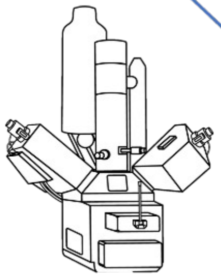
Hollow-core woodpile coupler – fabrication tests

FESEM characterization









Drying process by using a CPD instrument

Accelerating gradient comparison

$$Z_c = \frac{(E_0 T \lambda)^2}{P_{inj}}$$

Slotted waveguide	2D PhC waveguide	3D woodpile
Z_c = 1.5 kΩ	Z_c' = Zc h = 37.6 Ω	Z_c = 11.4 kΩ

P_{inj} = 250 W	P_{inj} = 250 W	P_{inj} = 500 W
E_0 = 0.4 GV/m @ λ = 1.55 μm	E_0 = 63 MV/m @ λ = 1.55 μm	E_0 = 1.63 GV/m @ λ = 1.55 μm
E_0 = 0.32 GV/m @ λ = 2 μm	E_0 = 48.5 MV/m @ λ = 2 μm	E_0 = 1.3 GV/m @ λ = 2 μm
E_0 = 0.13 GV/m @ λ = 5 μm	E_0 = 19.4 MV/m @ λ = 5 μm	E_0 = 0.5 GV/m @ λ = 5 μm

Example: 3D woodpile, E_0 = 0.5 GV/m @ λ = 5 μm.

To reach a final energy of 100 MeV, only a 21 cm long accelerating channel is sufficient.

Extremely-compact structure!