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Copropagating schemes for Dielectric Laser Accelerators

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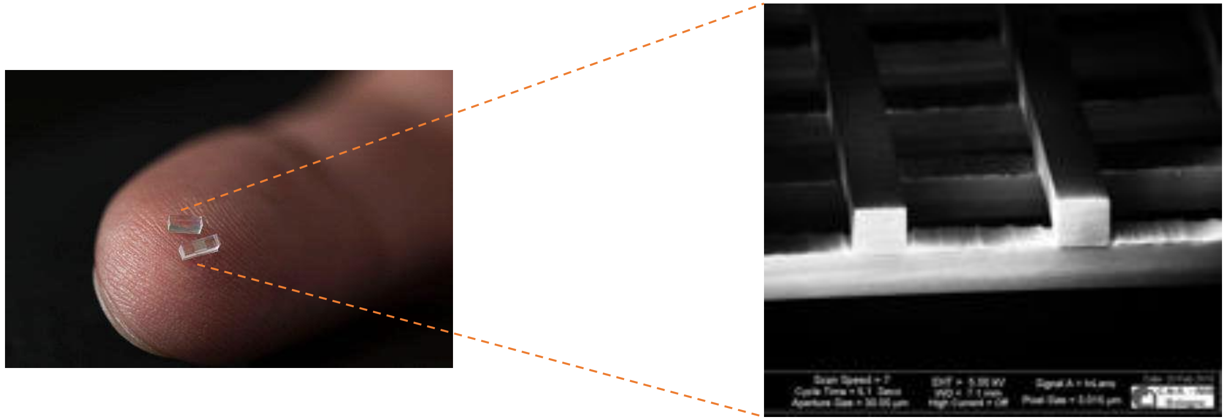


Dielectric Laser Accelerators (DLA) : introduction

- **MOTIVATION**: strong need of particle accelerators working at higher and higher frequencies (reaching optical frequencies) 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 optical application because of <u>electrical breakdown in metals</u> and their <u>high losses at optical frequencies</u>.

<u>SOLUTION: employing dielectric structures</u>

Main advantages of DLA:

a) **<u>larger damage threshold of dielectrics</u> near infrared with respect to metals;**

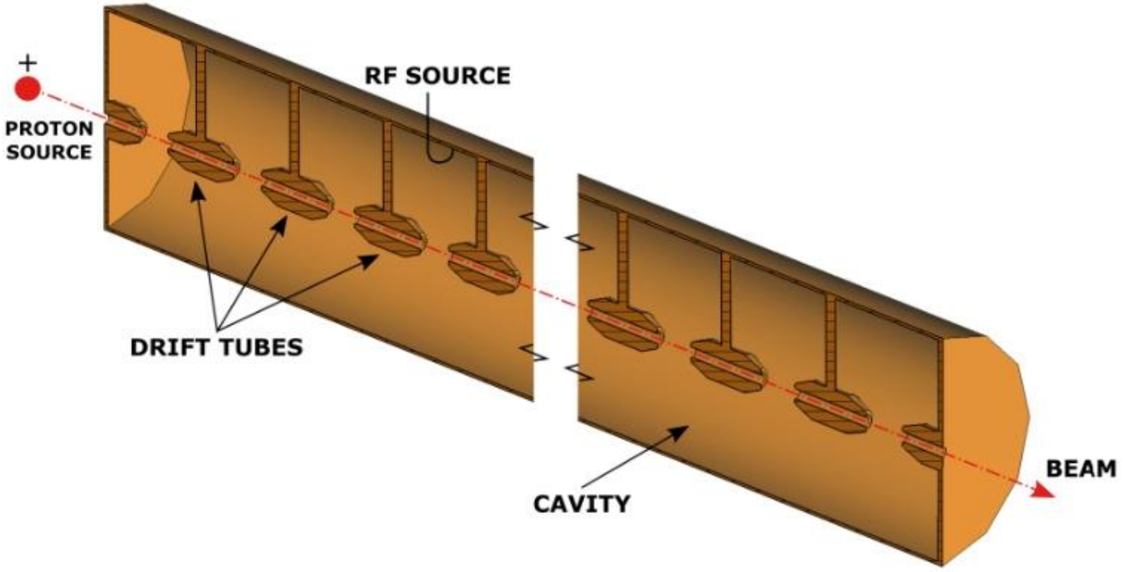
b) with the same maximum electric field (limited by the breakdown) **shorter wavelength means higher *accelerating gradients per unit length***;

c) consequential **<u>reduction of size and fabrication costs.</u>**

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

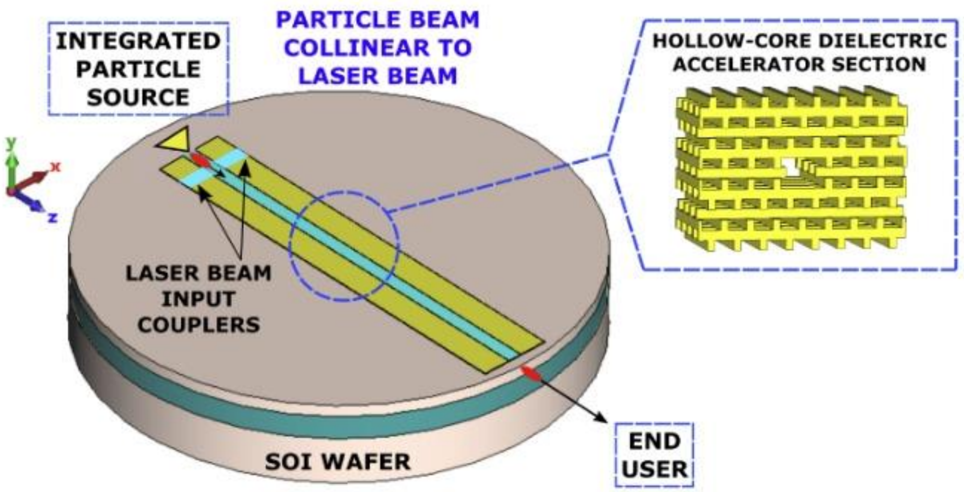
Dielectric Laser Accelerators (DLA) vs metallic accelerators

1 M€ CONVENTIONAL ACCELERATOR



Total length ~ 100 m

DLA ACCELERATOR 10 k€

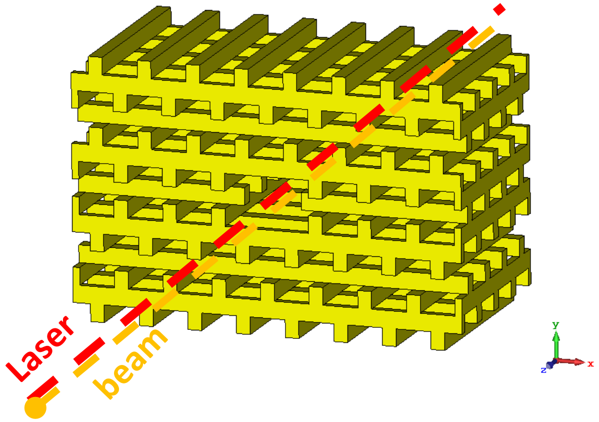


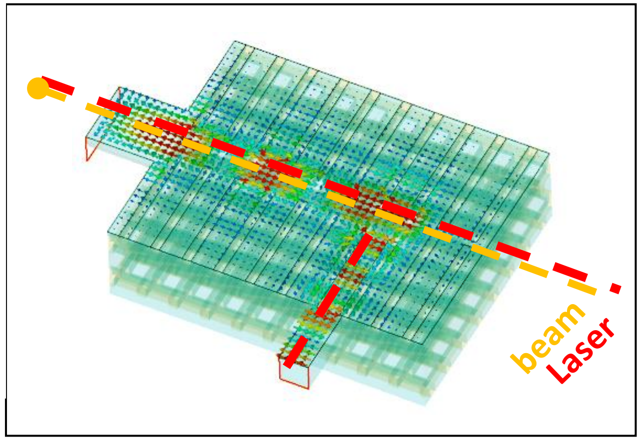
Total length ~ 10 cm

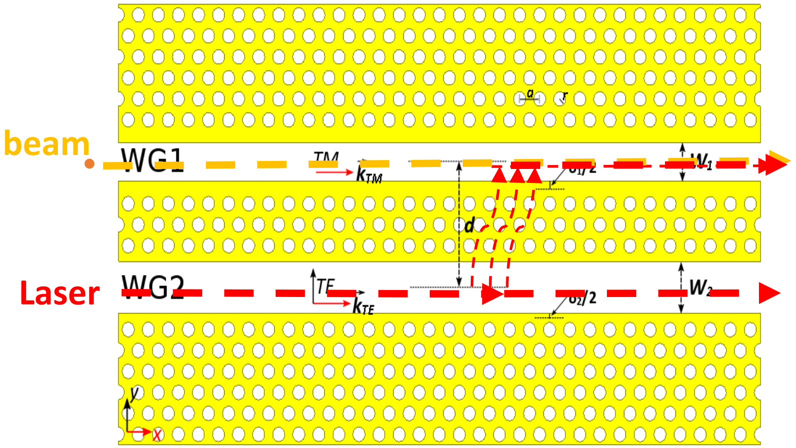
Copropagating schemes for Dielectric Laser Accelerators

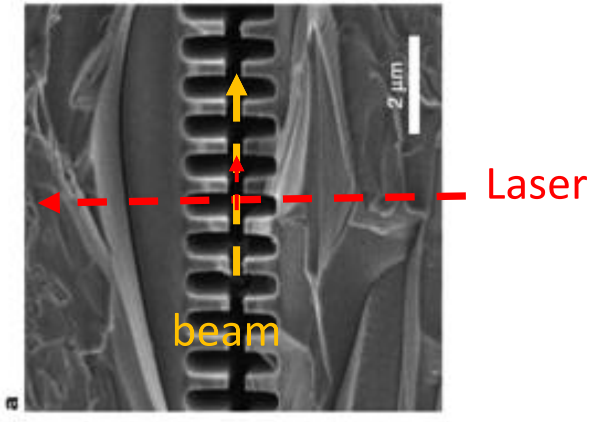
What we mean for ***Copropagating?***

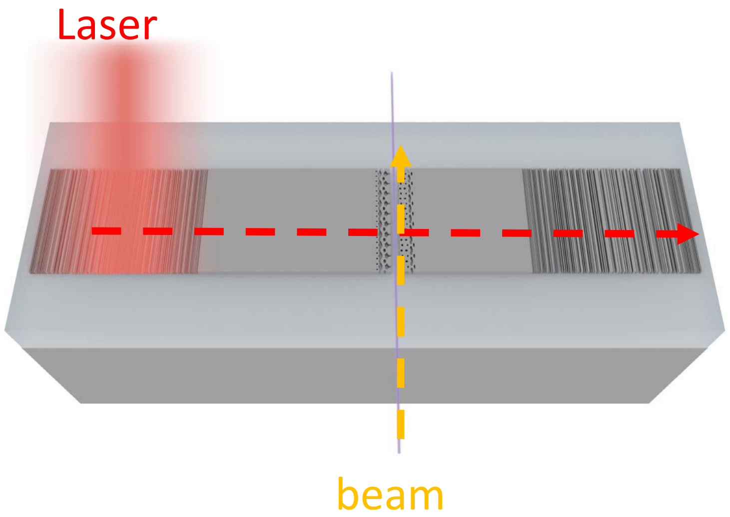
Copropagating schemes vs ***Cross-propagating schemes***



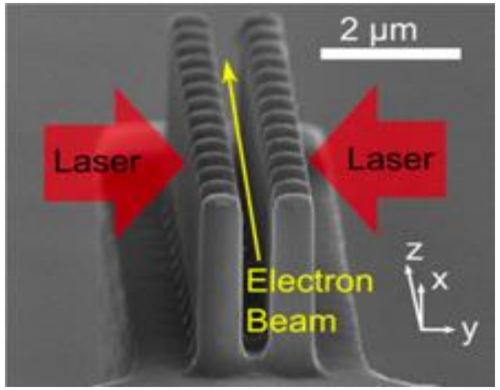


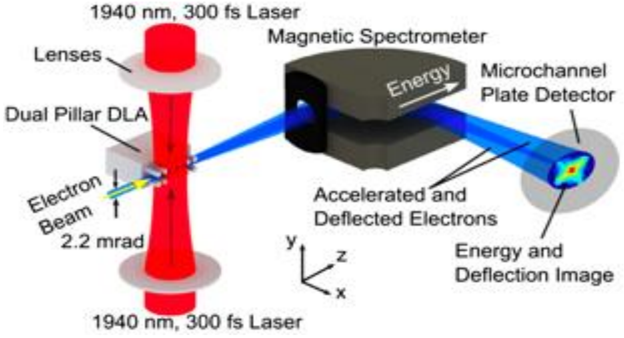






New Acceleration Concepts.
“Dielectric Laser Acceleration”, Joel England (SLAC)
Snowmass AF6 Meeting Sept 23, 2020]





Cross-propagating schemes

“transverse-illuminated” *Phase Reset Device*

↓

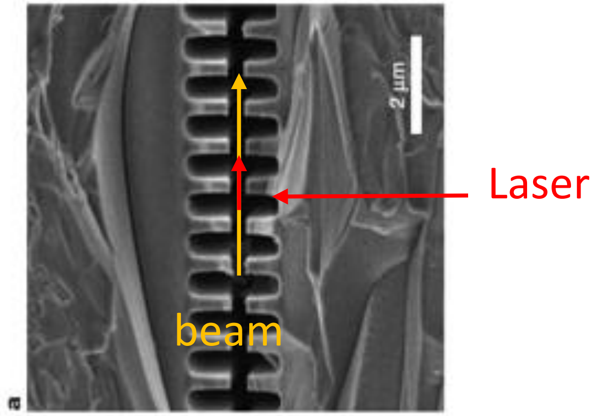
short interaction region
(few μm)

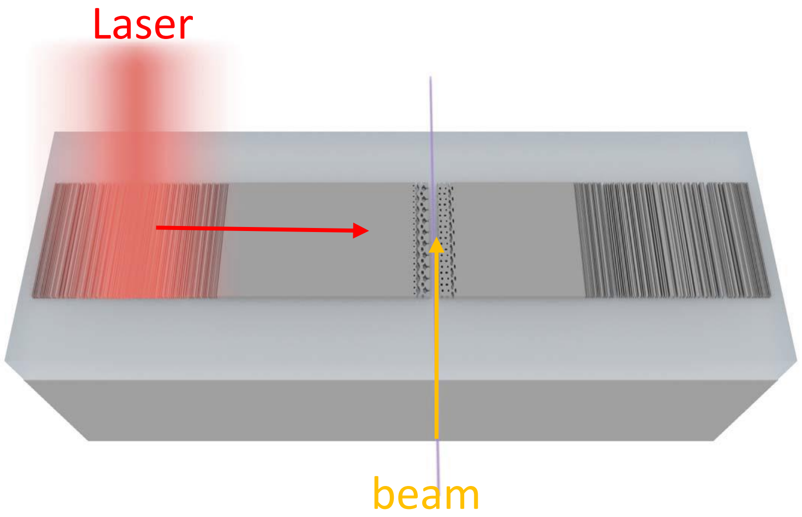
↓

low energy gain per stage
(few keV)

↓

cascading stages of acceleration is very challenging

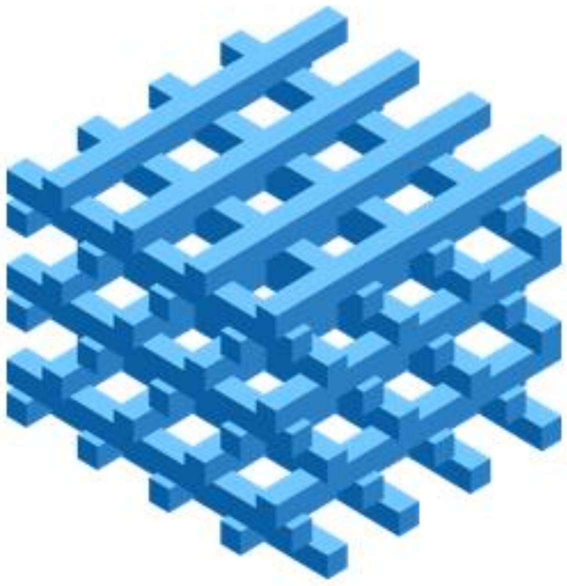




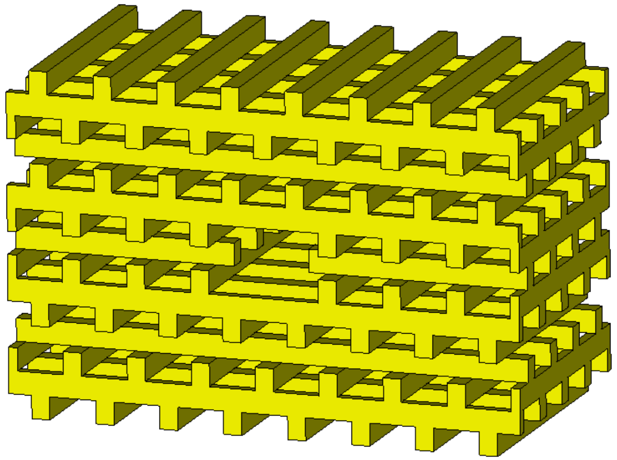
[N. V. Sapra et al; Science, 367, 6473, 79-83 2020]
[E. A. Peralta et al; Nature, 503(7474):91–94, 2013.]
[Kent P. Wootton et al; Opt. Lett., 41(12):2696, 2016]
[D. Cesar et al; Nature Comm. Phys., 1(4):1–7, 2018]
[K. J. Leedle et al; Opt. Lett., 40(18):4344, 2015]

Electromagnetic Band Gap (EBG) structures

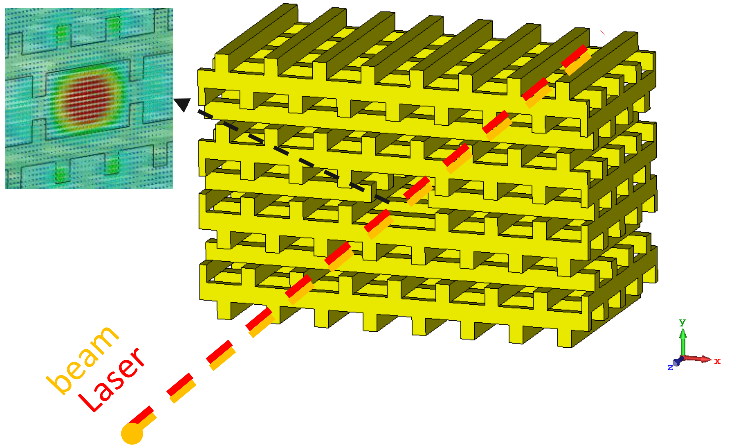
- **Periodic pattern of dielectric material that, for some frequency range, prohibits the propagation of electromagnetic waves, forming a band-gap.**



- **Introducing a defect into the structure**, by removing or altering one element of the structure, **a guided mode can be trapped inside the structure.**



Photonic Crystal (PhC)-based Dielectric Laser Accelerator (DLA)

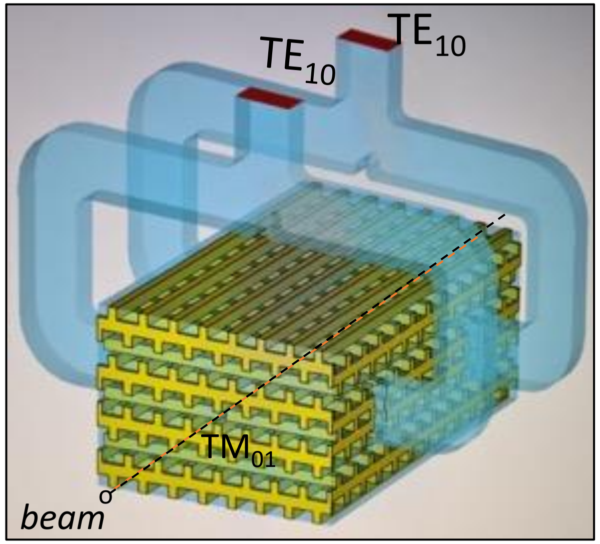


3D silicon ***woodpile waveguides***

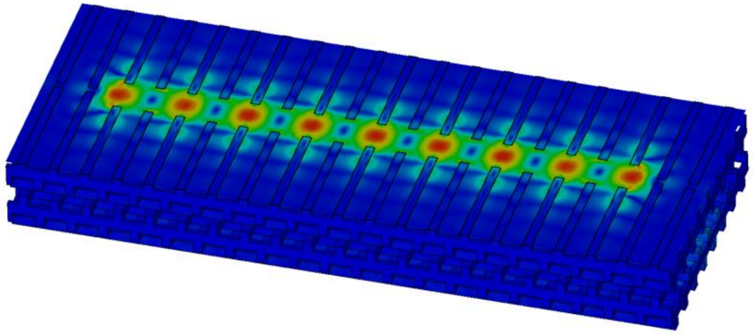
[G. S. Mauro et al., " in IEEE MTT, 68, 5, 1621-26, 2020]
[G. Torrisi *et al*., *IEEE MWCL*, 30, 4, 347-350, 2020]

<u>Copropagating</u> schemes

- **Hollow-core waveguides** for <u>high power handling</u>
- **Collinear** <u>co-propagating</u> laser and particle beam
- **<u>High interaction impedance</u>** $\mathbf{Z_c}$ and **accelerating gradient**
- **<u>Continuous wave</u>** <u>(CW)</u> laser operation (1-5 μm)

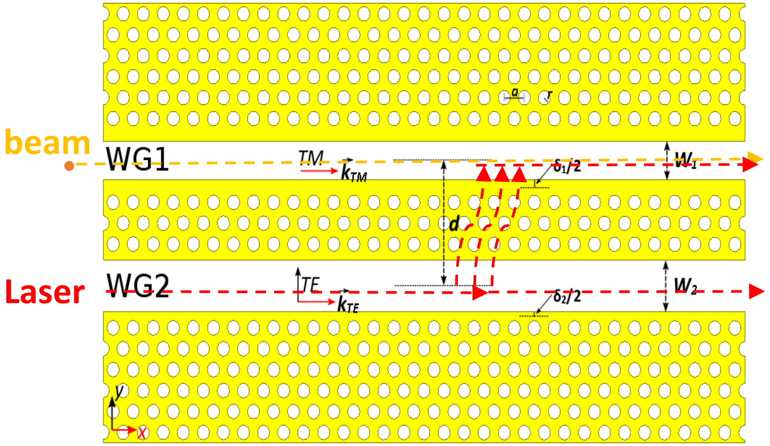


3D Silicon ***woodpile mode launcher***

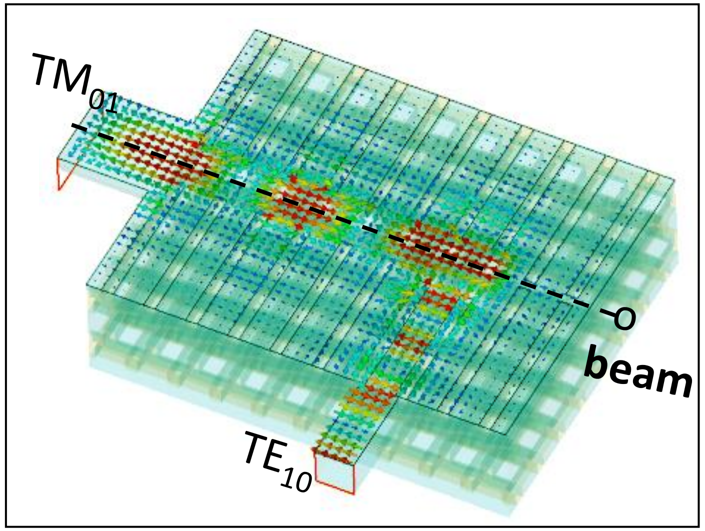


3D silicon ***woodpile cavity***
(in development…)

2D *longitudinal Photonic Crystal*
Directional Coupler



[G. Torrisi *et al* 2019 *J. Phys.: Conf. Ser.* **1350** 012060]



3D woodpile mode converter

[G. S. Mauro et al;. 15th Metamaterials Conf. (Aug. 2021)]
[Ziran Wu et al; Phys. Rev. ST Accel. Beams 17, 081301]

Copropagating schemes for Dielectric Laser Accelerators

What we mean for ***schemes?***

We require:
1. an optical waveguide that is constructed out of dielectric materials;
2. transverse size on the order of a wavelength;
3. a supported mode with speed-of-light phase velocity in vacuum.

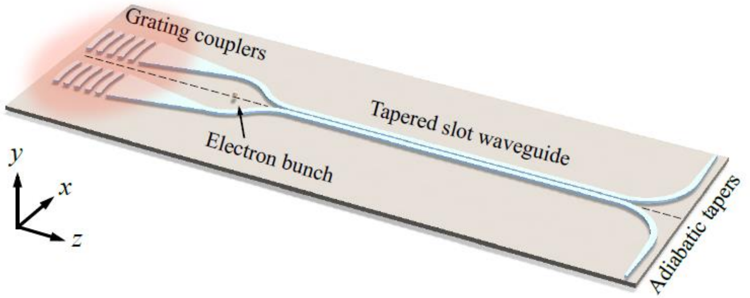
↓

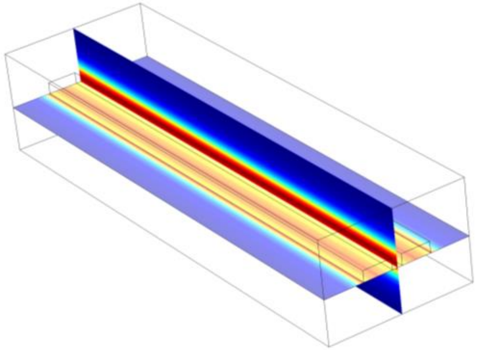
Photonic crystals - structures whose electromagnetic properties are spatially periodic - can meet these requirements.

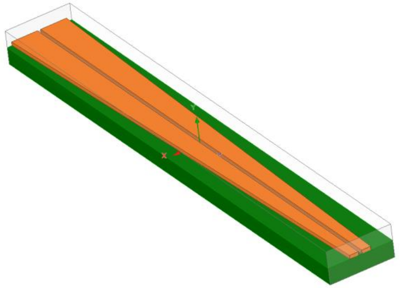
Copropagating schemes for Dielectric Laser Accelerators

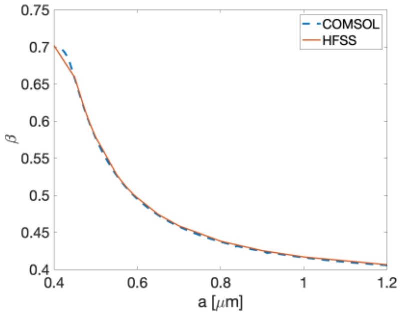
What we mean for *schemes?*

1) Slotted waveguide @ 5 μm
$[0.4 < \beta < 0.75,\ Zc = 1.5\ \mathrm{k\Omega}]$

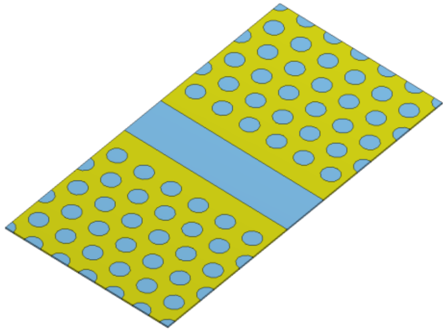


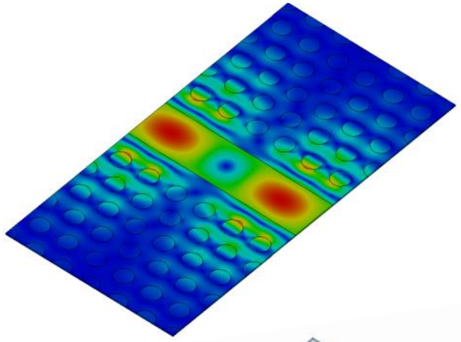


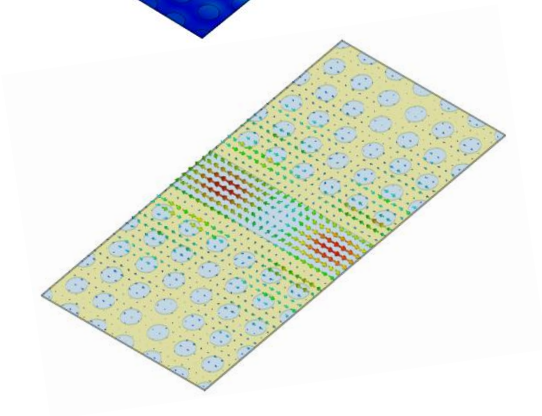




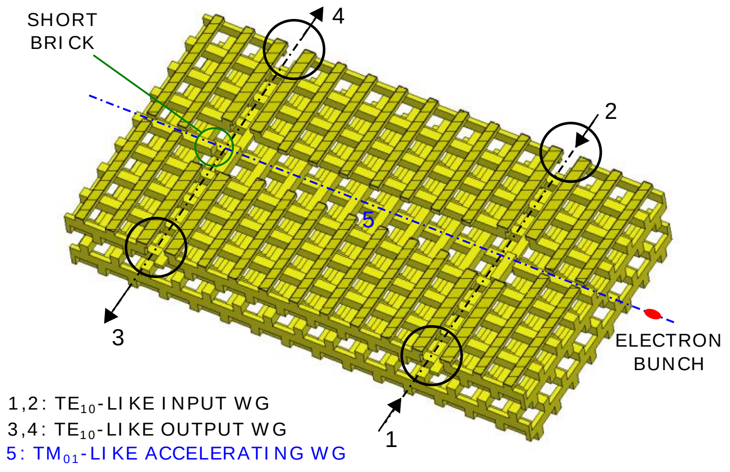
2) 2D PhC waveguide @ 5 μm
$[\beta = 1]$

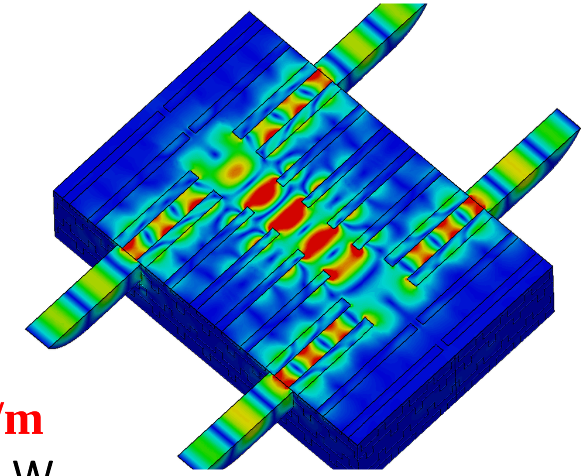






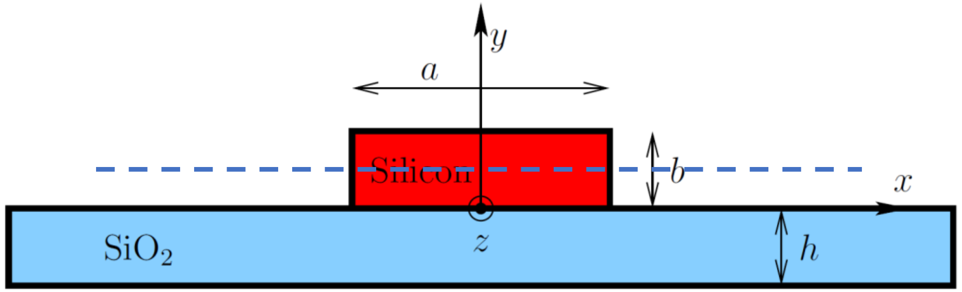
3) Woodpile @ 5 μm
$[\beta = 1, Z_c = 11.4\ \mathrm{k\Omega}]$



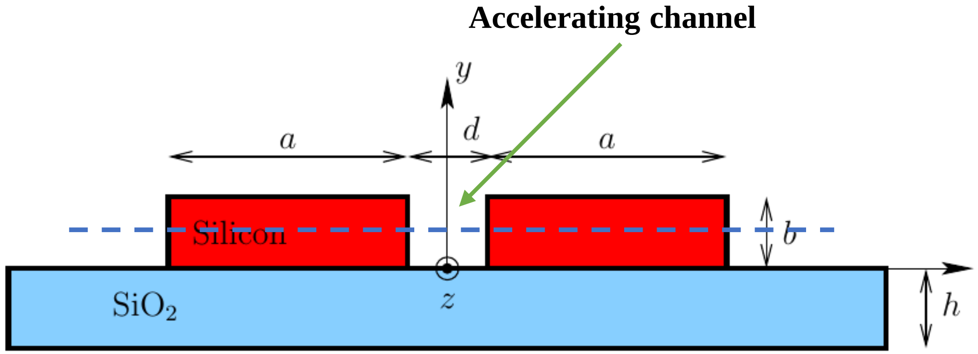


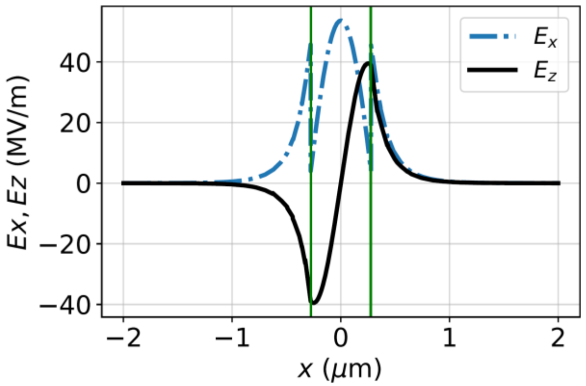
$E_0 \sim 1$ GV/m
@ $P_{INJ} = 500$ W

Solid core waveguides

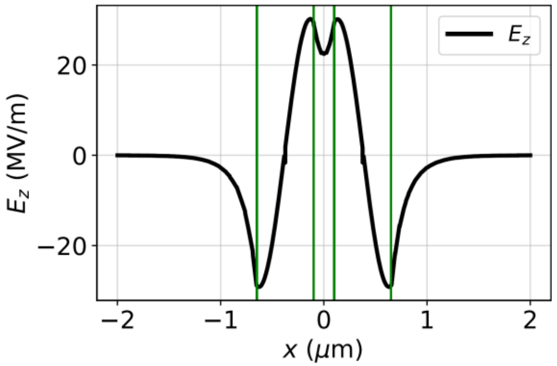


Solid core waveguide, doesn't allow particle transit

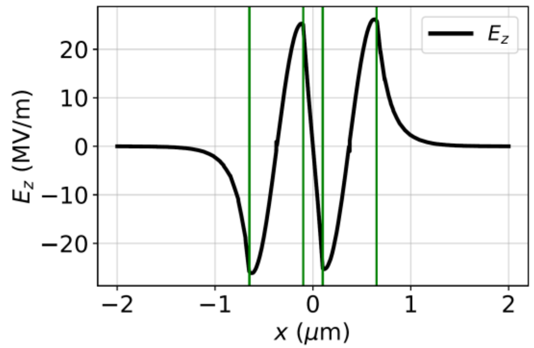


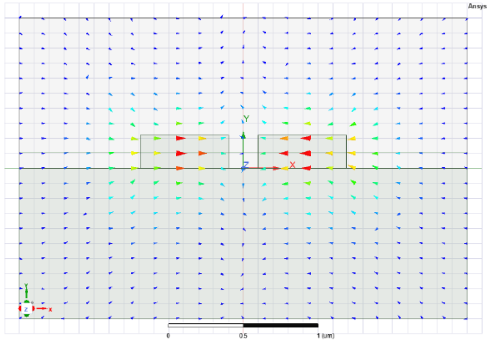


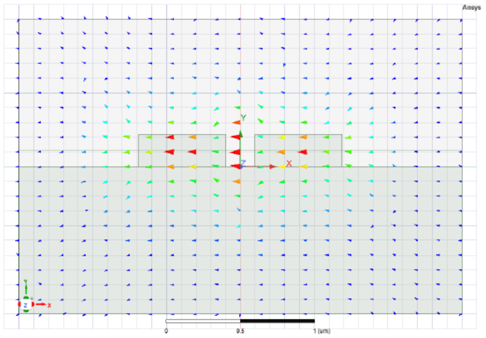
"Accelerating" mode - electric field Ez component (odd symmetry)



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





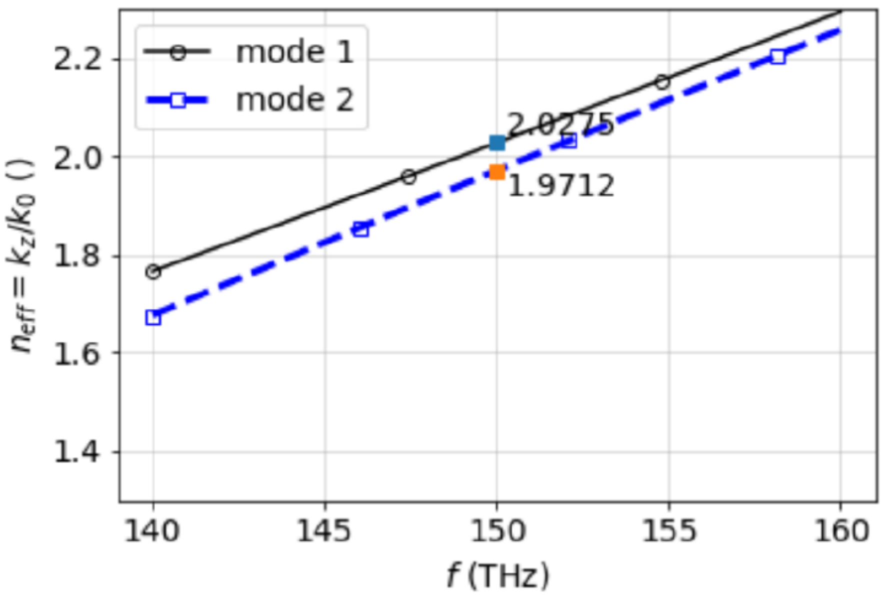


Zhao et al., «Design of a tapered slot waveguide dielectric laser accelerator for sub-relativistic electrons»; 2018

Slotted waveguide

Effective index computation

Simulators	$n_{eff,mode1}$	$n_{eff,mode2}$
COMSOL	2.04	1.99
HFSS	2.0275	1.9712
MATLAB(Full vector)	2.155726	2.106516

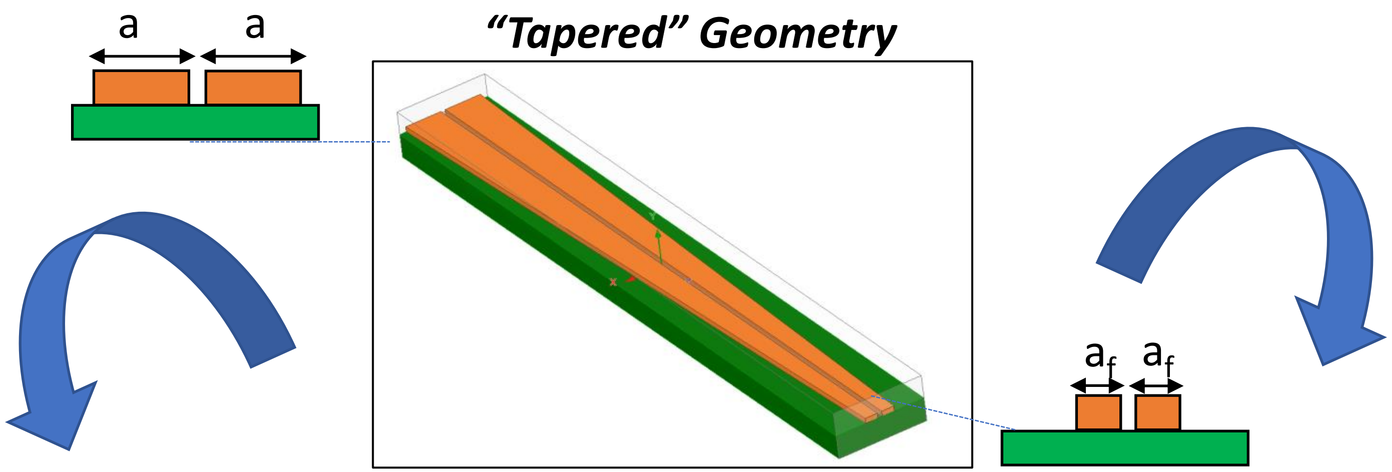


Mode 1: **"fundamental"** mode (even symmetry)
Mode 2: **"accelerating"** mode (odd symmetry)

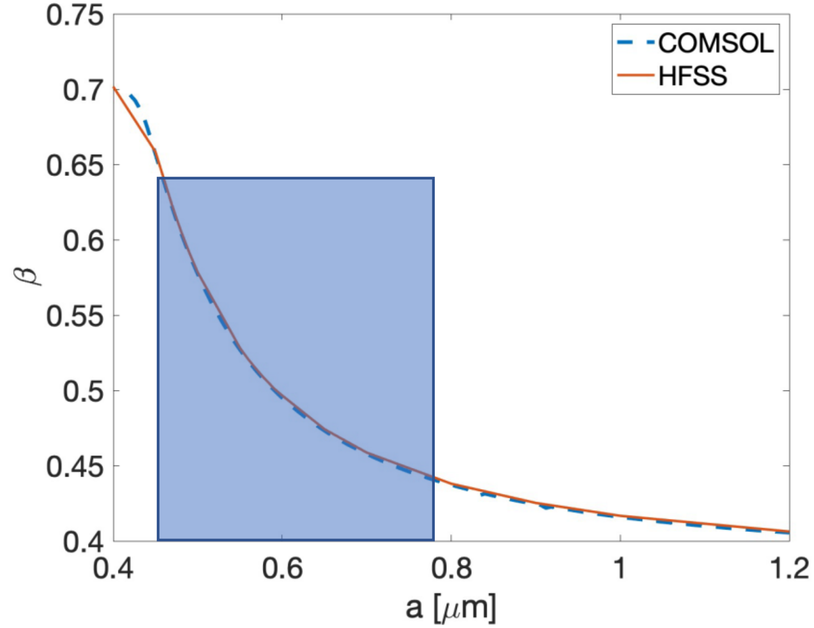
Very close but **selectable** thanks to the launching **"even/odd" Excitation field**

f = 150 THz → $n_{eff} = 1.9712$ → $\boldsymbol{\beta = \frac{v}{c} = \frac{c/n_{eff}}{c} = 0.5}$

Tapered slot waveguide for sub-relativistic electrons



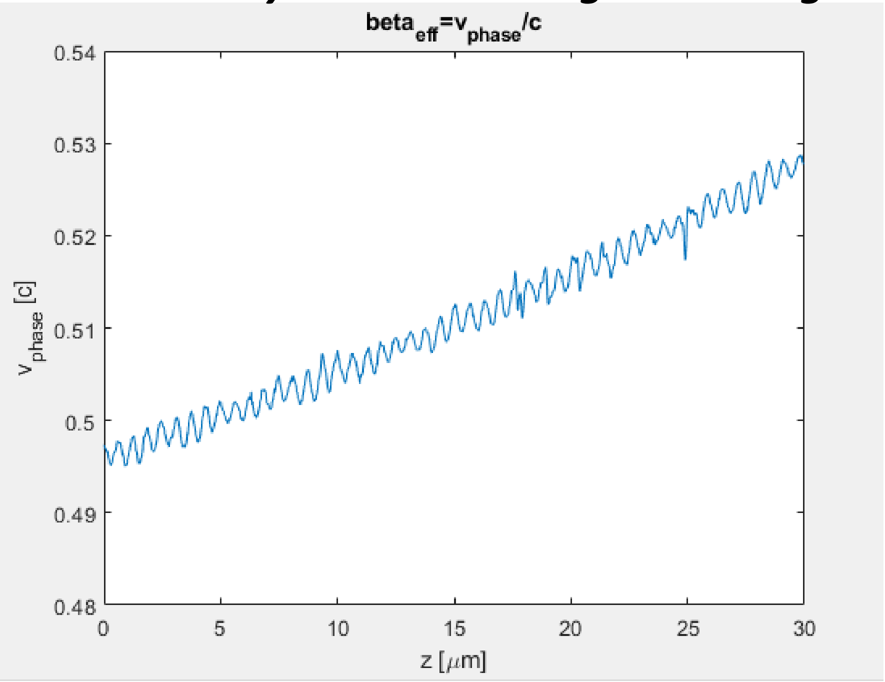
β variation due to the slot width size a tapering: the structure 'follows' the electron energy increase due to acceleration.



Slotted waveguide
"safe" range
$$0.4 < \beta < 0.63$$

a (μm)	β	$E_{total}(KeV)$
0.47	0.62	140.47
0.50	0.58	116.44
0.55	0.53	91.72
0.59	0.50	79.16
0.60	0.495	77.21
0.80	0.44	58.12

Phase velocity variation along the waveguide



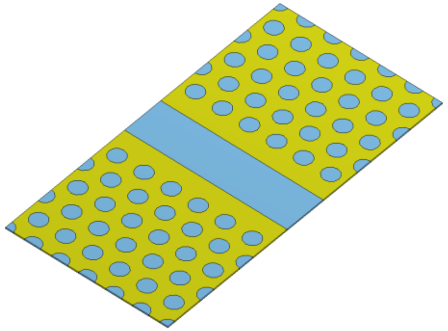
Copropagating schemes for Dielectric Laser Accelerators

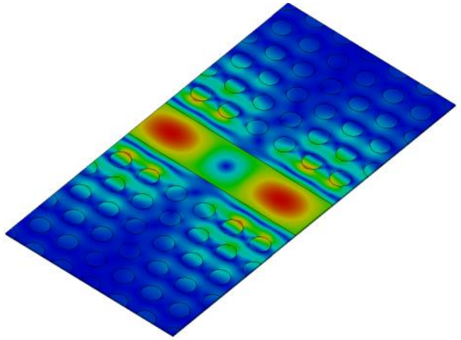
1) Slotted waveguide @ 5 μm

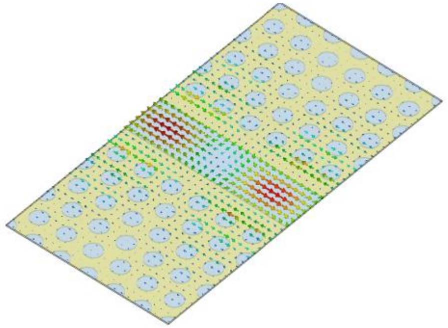
$[0.4 < \beta < 0.75,\ Zc$=1.5 kΩ]

2) 2D PhC waveguide @ 5 μm

$[\boldsymbol{\beta} = \mathbf{1}]$







3) Woodpile @ 5 μm

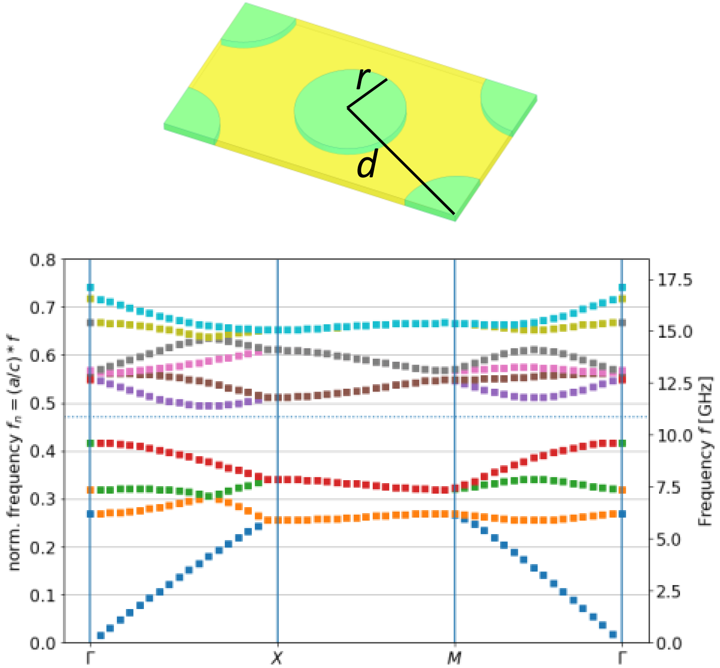
$[\boldsymbol{\beta} = \mathbf{1}, Z_c$ = 11.4 kΩ]

$E_0 \sim$ 1 GV/m

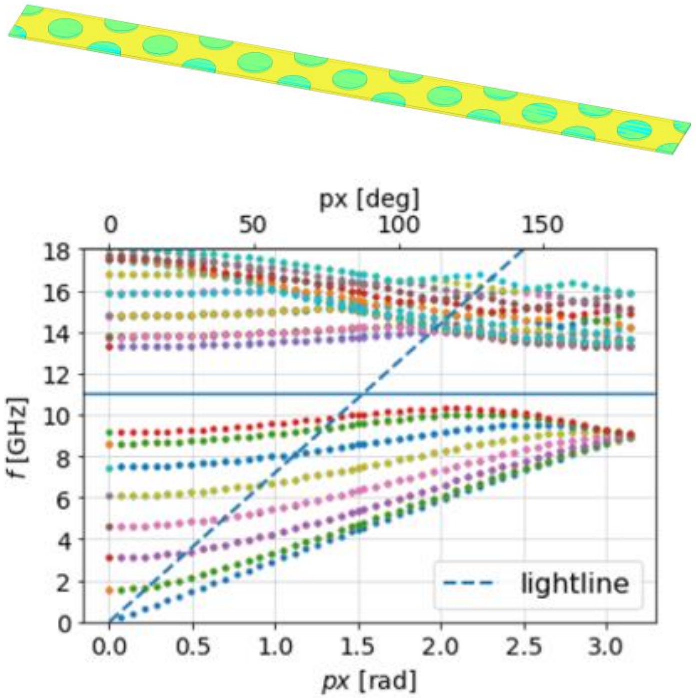
@ P_{INJ} = 500 W

2D photonic crystal waveguide

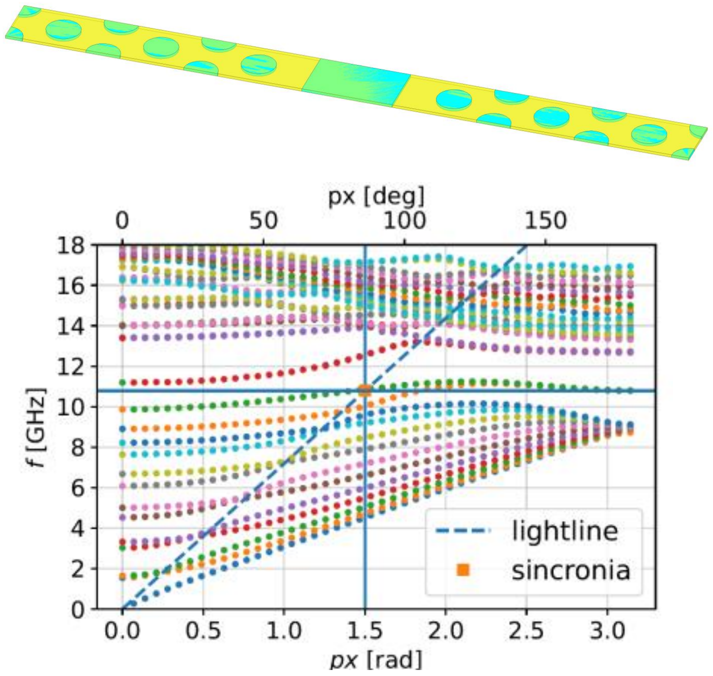
a) computation of the **band diagram** of the triangular lattice primitive cell



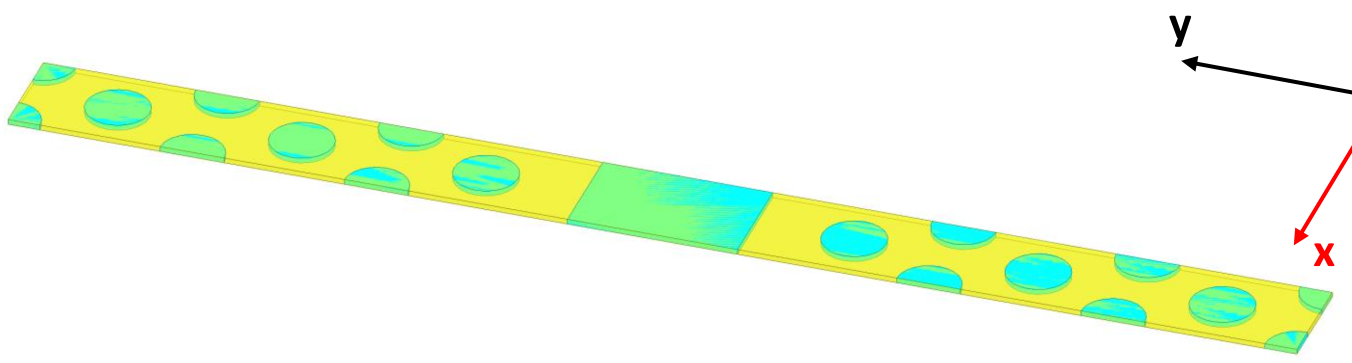
b) computation of the **projected band diagram** of a triangular lattice supercell

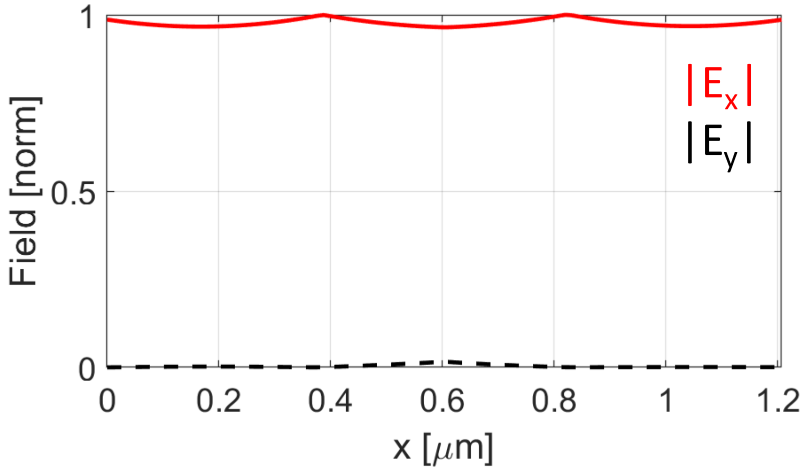


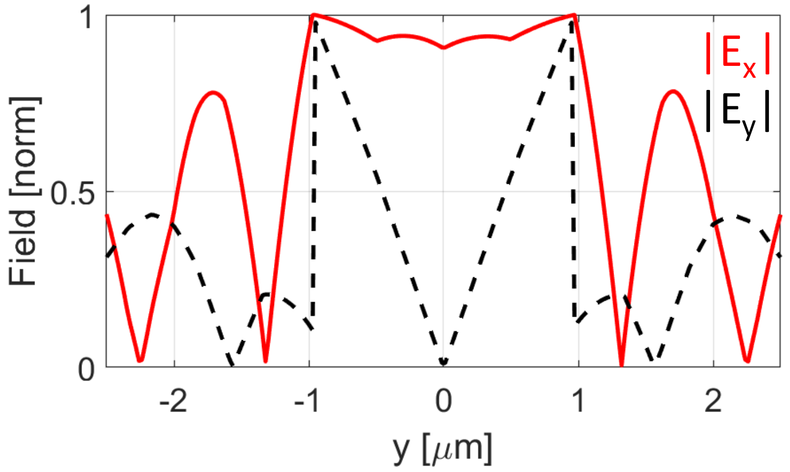
c) add a **hollow-core linear defect** to the supercell



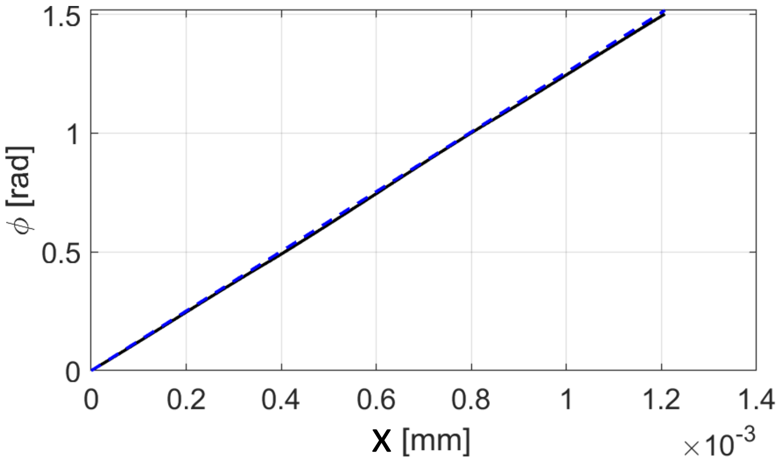
2D photonic crystal waveguide





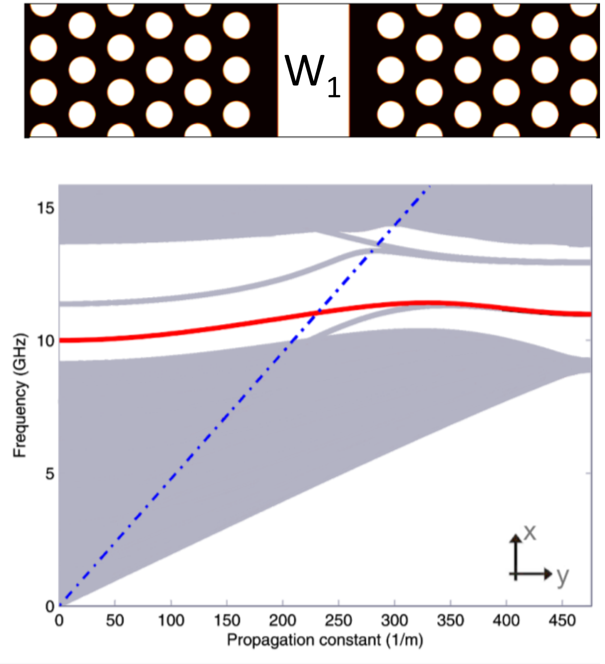


Phase of E_x along x vs. $\frac{\omega}{c}x$

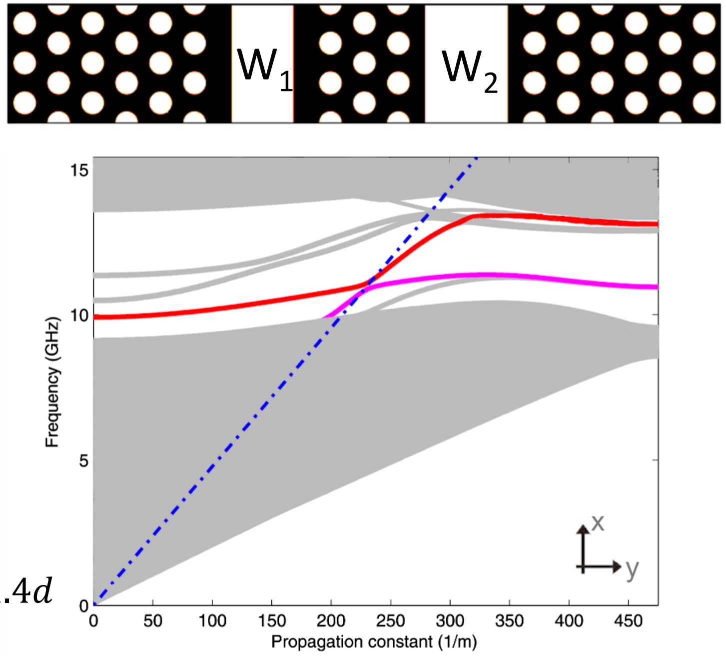


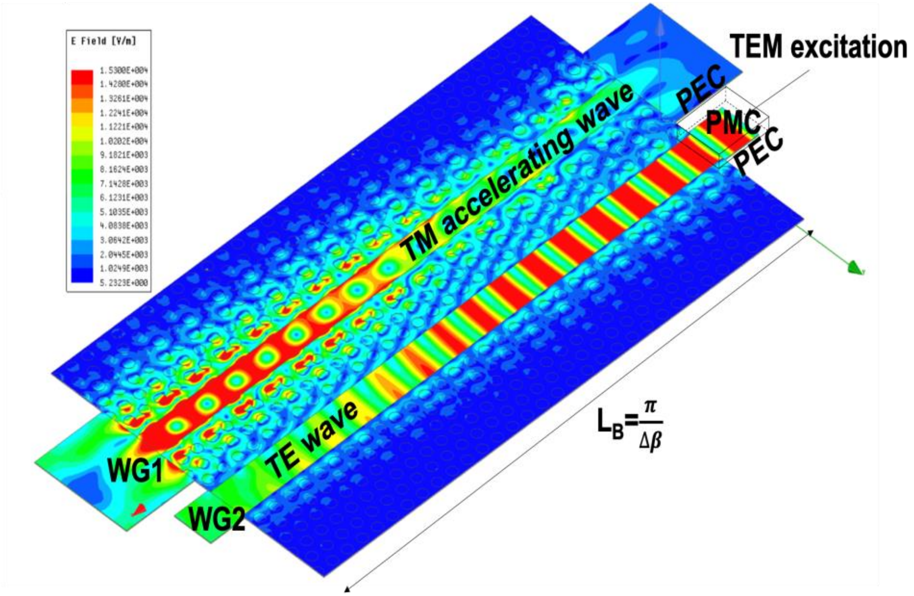
2D photonic crystal waveguide coupler

- Efficient coupling between the **launch** and the **accelerating** waveguide.
- 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 varying W.
- When the waveguides couple, efficient energy exchange is possible.



$$L_B = \frac{\pi}{\Delta\beta} = 31.4d$$





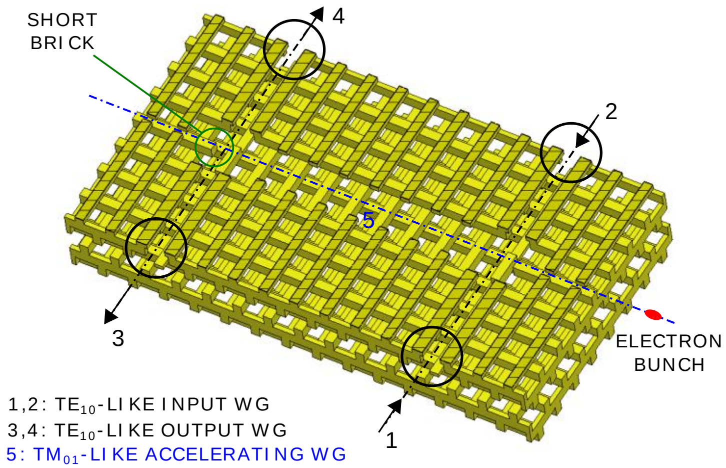
Locatelli et al., «Photonic crystal waveguides for particle acceleration»; 2017

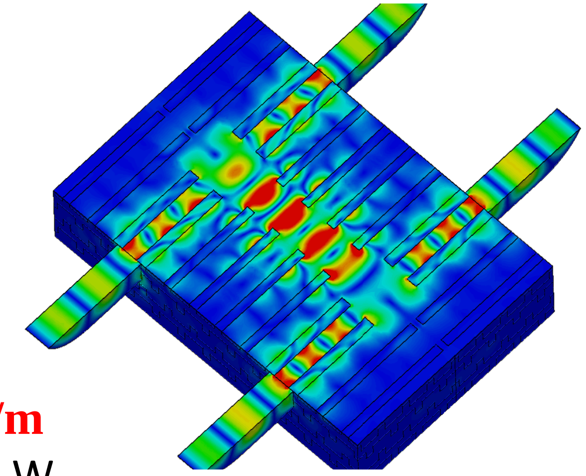
Copropagating schemes for Dielectric Laser Accelerators

1) Slotted waveguide @ 5 μm
$[0.4 < \beta < 0.75,\ Zc=1.5\ \text{k}\Omega]$

2) 2D PhC waveguide @ 5 μm
$[\beta = 1]$

3) Woodpile @ 5 μm
$[\boldsymbol{\beta} = \mathbf{1}, Z_c = 11.4\ \text{k}\Omega]$





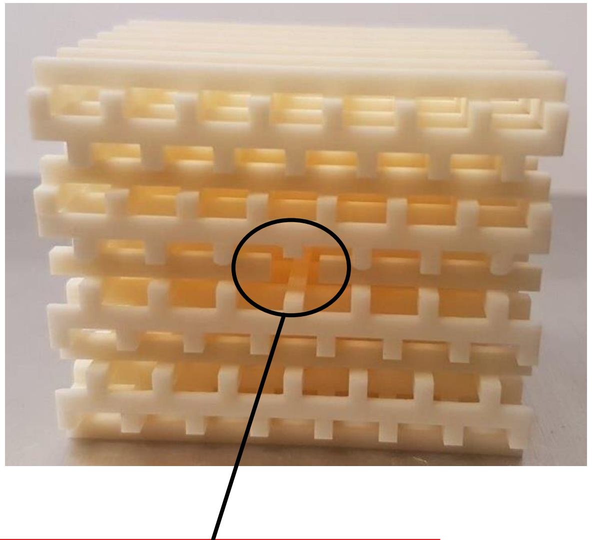
$\mathbf{E_0 \sim 1\ GV/m}$
@ P_{INJ} = 500 W

3D woodpile structure

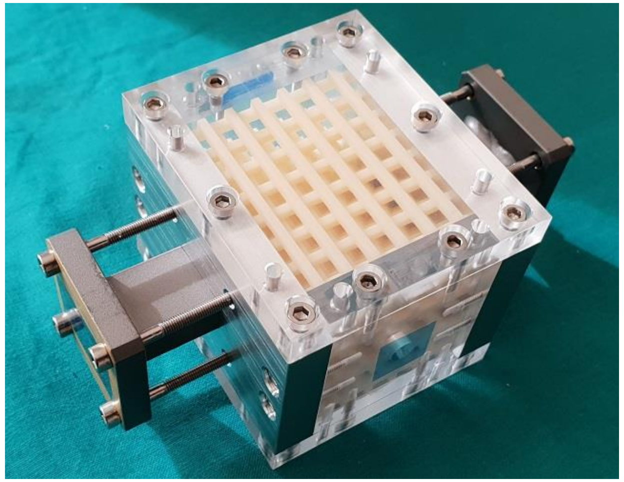
- Composed by a “pile” of rectangular $w \times h$ bricks disposed in layers stacked in the vertical direction, each layer rotated of 90° with respect from the layer below, whose centers are distant a period d.

- Creating a so called “defect channel”, one or more modes can be trapped inside the defect and thus a waveguide is obtained.

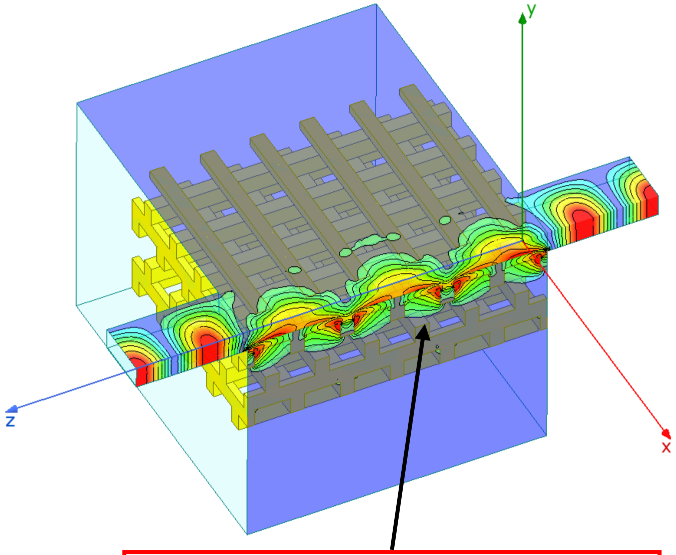
- The guided mode can be either a ‘launch’ transverse electric mode (TE10-like) or a mode suitable for particle acceleration (TM01-like).



‘Hollow-core’ defect channel



Woodpile waveguide



Electric field inside defect channel

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

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

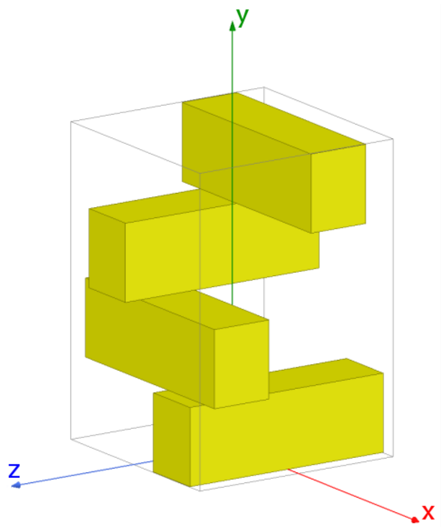
- The band-gap can be calculated using the MIT Photonic Bands (MPB) tool considering an **unit cell with periodic boundary conditions**.

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

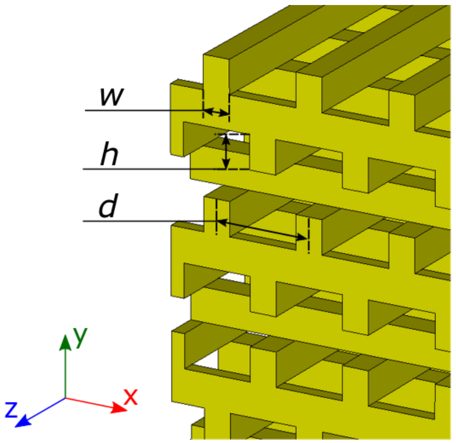
- Once the fundamental (normalized) parameters have been obtained, the structure can be scaled at the **final operating frequency**.

- 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**.

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



Woodpile unit cell



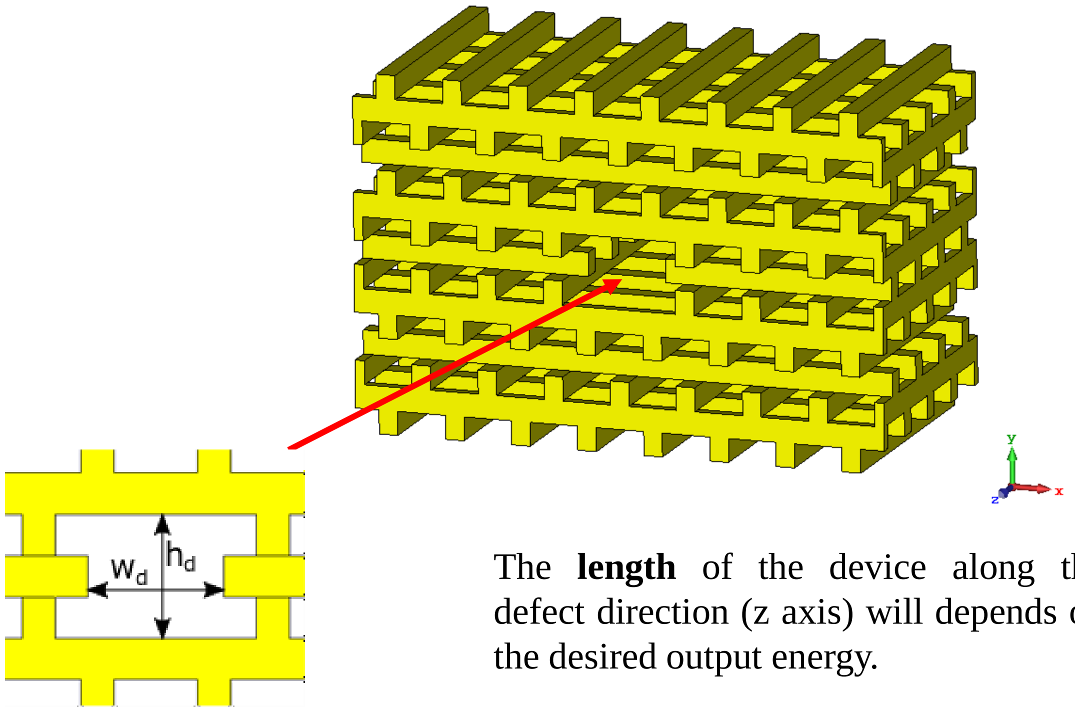
width (**w**) = 588 nm

height (**h**) = 736 nm

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.

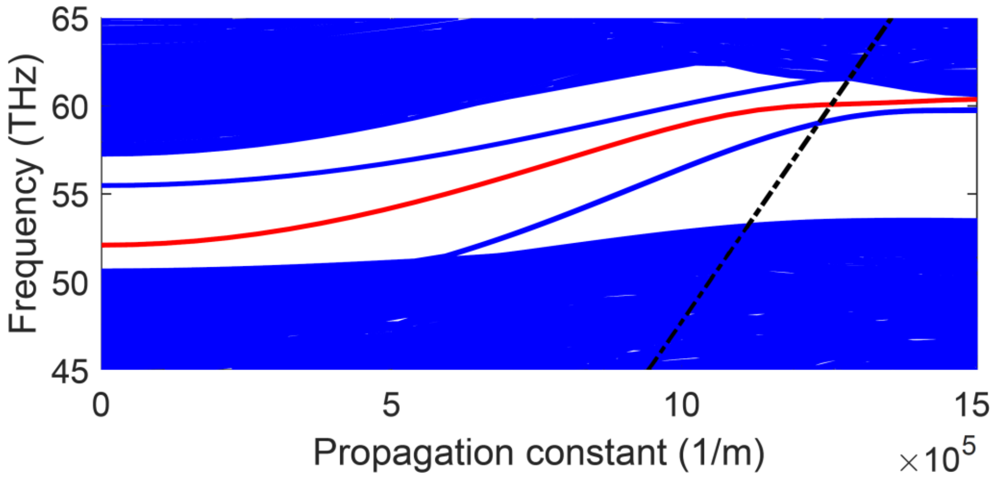
- This defect can be tuned to support an electromagnetic mode that can be guided along the structure in the way to form a waveguide.



Hollow core defect dimensions:

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

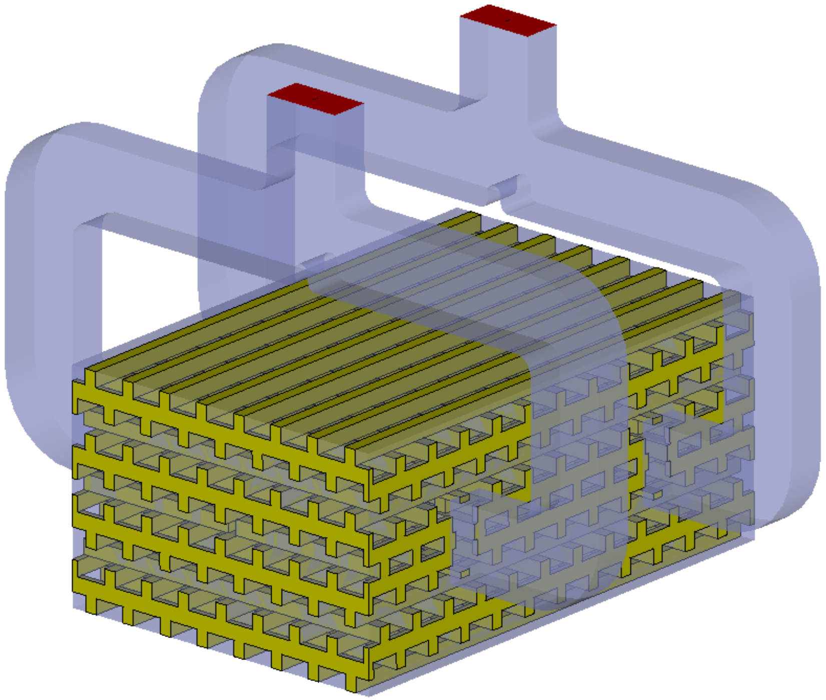
The **length** of the device along the defect direction (z axis) will depends on the desired output energy.



'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.

5000 nm hollow-core woodpile coupler



Structure dimensions: **5.2um x 7.8um x 3.42 um**

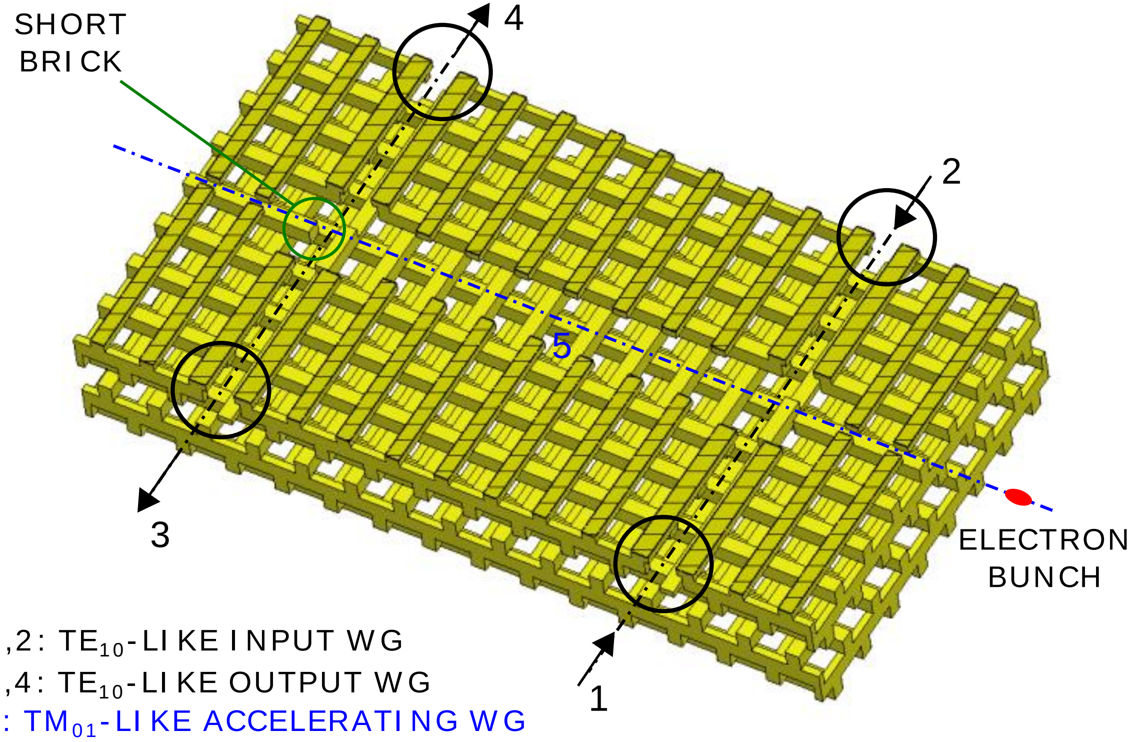
- Wave is injected (and extracted) into the woodpile coupler by using two waveguide **splitters** (or optical fibers at optical frequencies).

- The bunch of particles is accelerated by the travelling wave along the hollow-core accelerating waveguide.

- 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

5000 nm hollow-core woodpile coupler

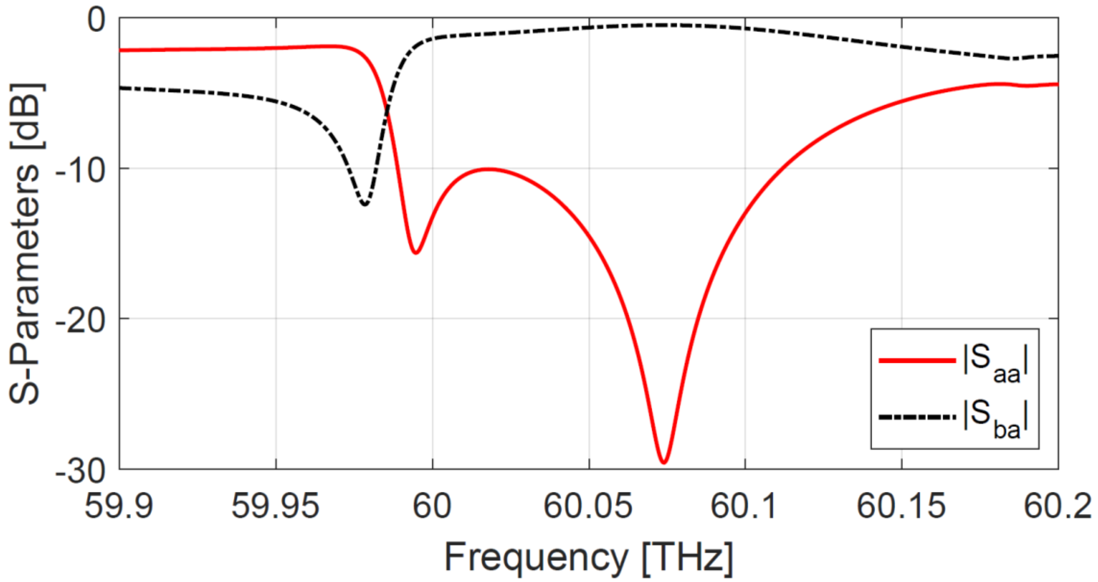
- Woodpile coupler tuned, in terms of S-parameters, to:

a) **maximize the I/O wave transmission;**

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

- The device possesses low loss (< 0.1 dB) inside the **operational bandwidth of 60.06-60.08 THz**.

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

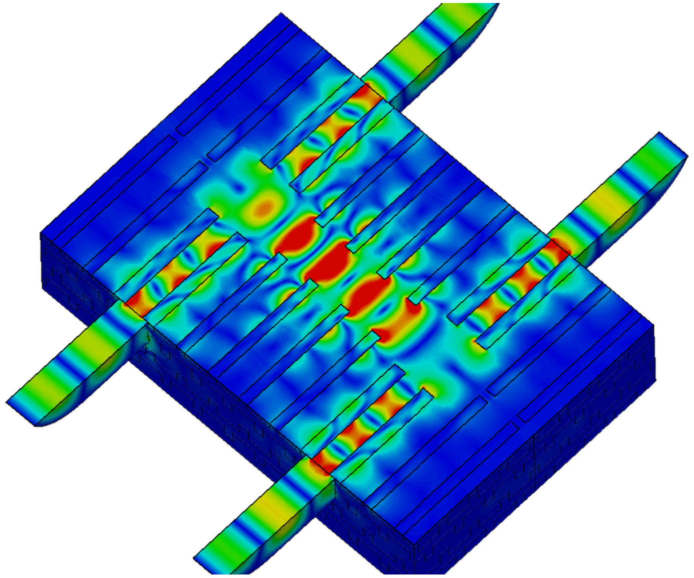


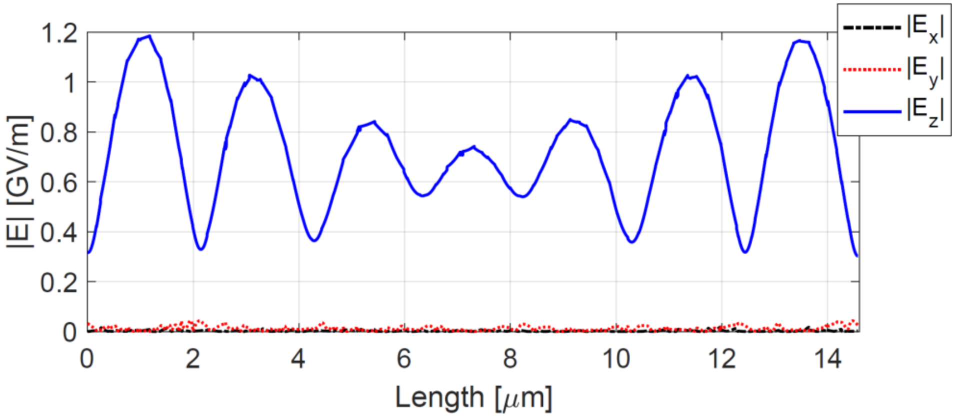
5000 nm hollow-core woodpile coupler

- From the electric field plot along the accelerating waveguide (**length** 3d = **1935 nm**), it can be seen that:

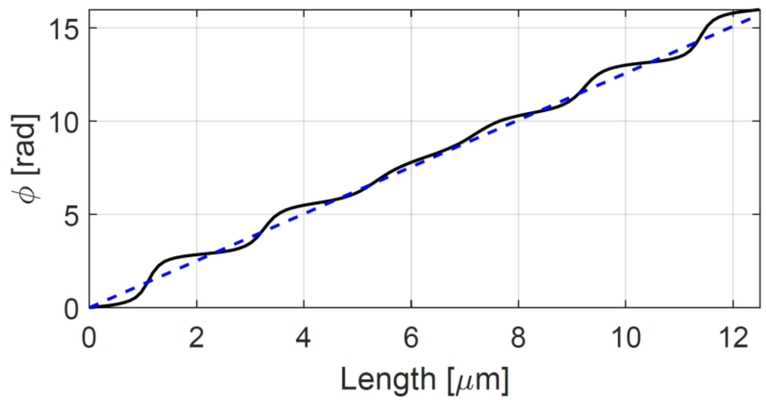
a) the longitudinal component |Ez| is predominant;

b) the transversal components |Ex|, |Ey|, are almost equal to zero.





Acc. gradient of 1 GV/m along hollow-core channel with 500 W input power.



TM01-like mode synchronous with speed of light @ 60 THz.

Accelerating gradient comparison

Slotted waveguide	2D PhC waveguide	3D woodpile
Zc = 1.5 kΩ	Zc’ = Zc × h = 37.6 Ω	Zc = 11.4 kΩ

P_{inj} = 250 W	P_{inj} = 250 W	P_{inj} = 500 W
E0 = 0.4 GV/m @ λ = 1.55 μm	E0 = 63 MV/m @ λ = 1.55 μm	E0 = 1.63 GV/m @ λ = 1.55 μm
E0 = 0.32 GV/m @ λ = 2 μm	E0 = 48.5 MV/m @ λ = 2 μm	E0 = 1.3 GV/m @ λ = 2 μm
E0 = 0.13 GV/m @ λ = 5 μm	E0 = 19.4 MV/m @ λ = 5 μm	E0 = 0.5 GV/m @ λ = 5 μm

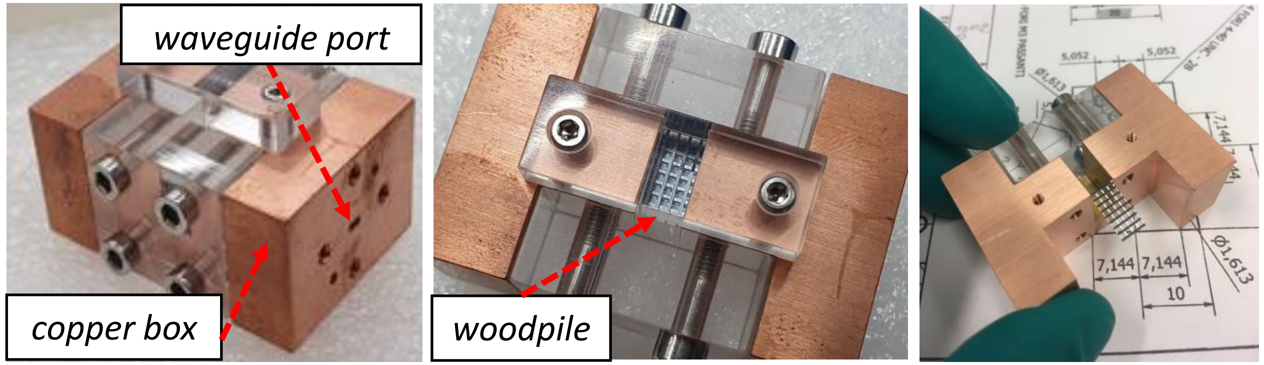
Example: 3D woodpile, E0 = 0.5 GV/m @ λ = 5 μm.

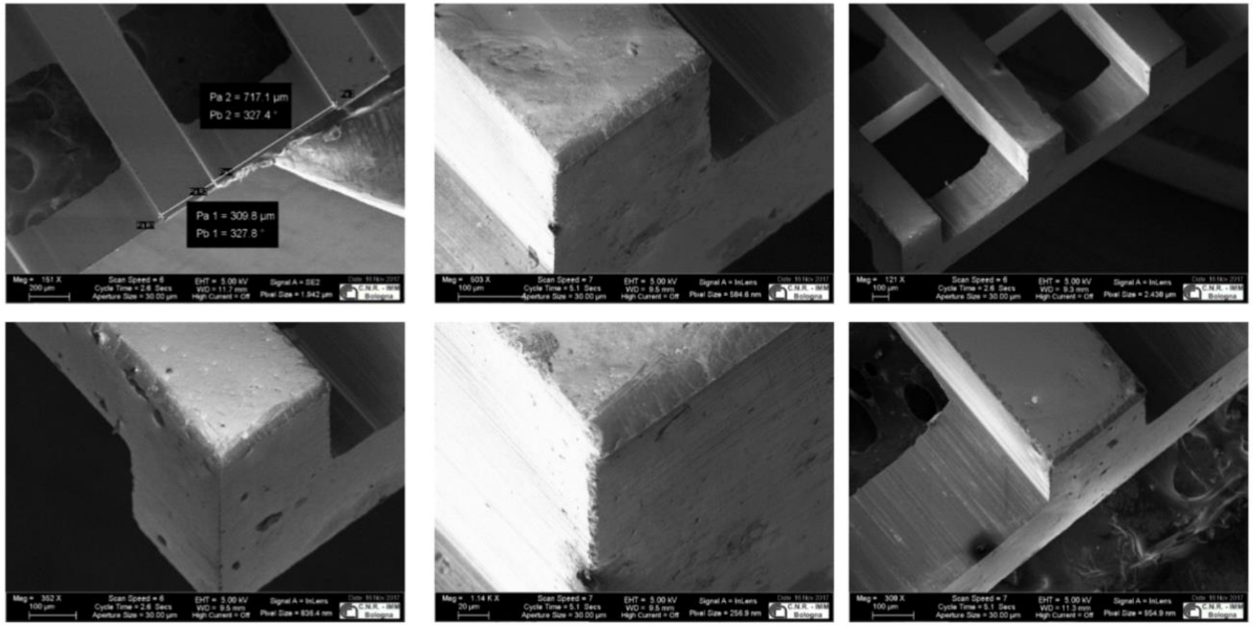
To reach a final energy of 100 MeV, only a 21 cm long accelerating channel is sufficient.

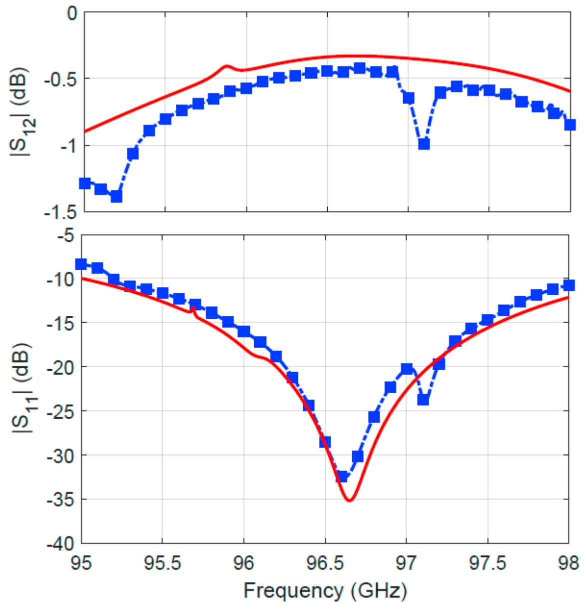
Extremely-compact structure!

Silicon woodpile waveguide: fabrication & cold test at scaled at mm-wave frequencies

- high speed and **precision dicing saws**
- **silicon wafers** 850 µm thick
- **stacking together 9 silicon** layers
- **geometrical tolerance of 10 µm**







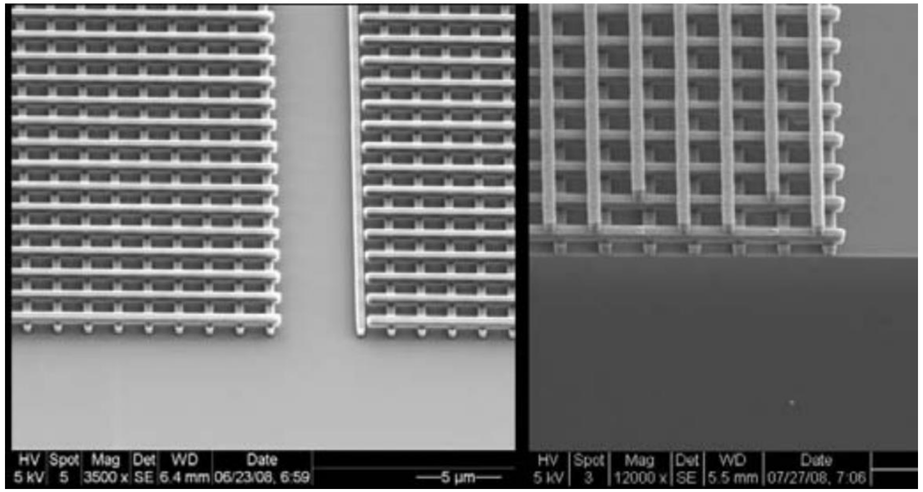
Simulated* vs *Experimental
S-parameters

Design is frequency independent and valid at any working wavelength.

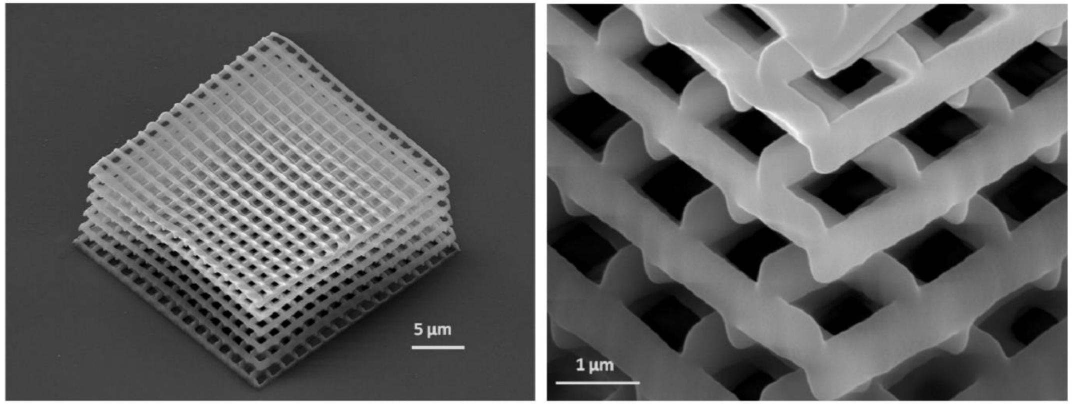
[G. Torrisi *et al.*, *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 4, pp. 347-350, 2020]

Woodpile structure fabrication - overview

- **Layer deposition (min. feature size: 450 nm)**
  - General process involves building up the structure layer by layer, using silicon dioxide as a matrix in which silicon features are embedded.
  - Then, a selective etch is done to remove the silicon dioxide, resulting in a free standing structure of silicon and vacuum.



- **Direct laser writing (min. feature size: 100 nm)**
  - 3D printing for the microscopic world.
  - By moving the focus of the laser beam three dimensionally, arbitrary 3D structures can be written into the volume of the material.

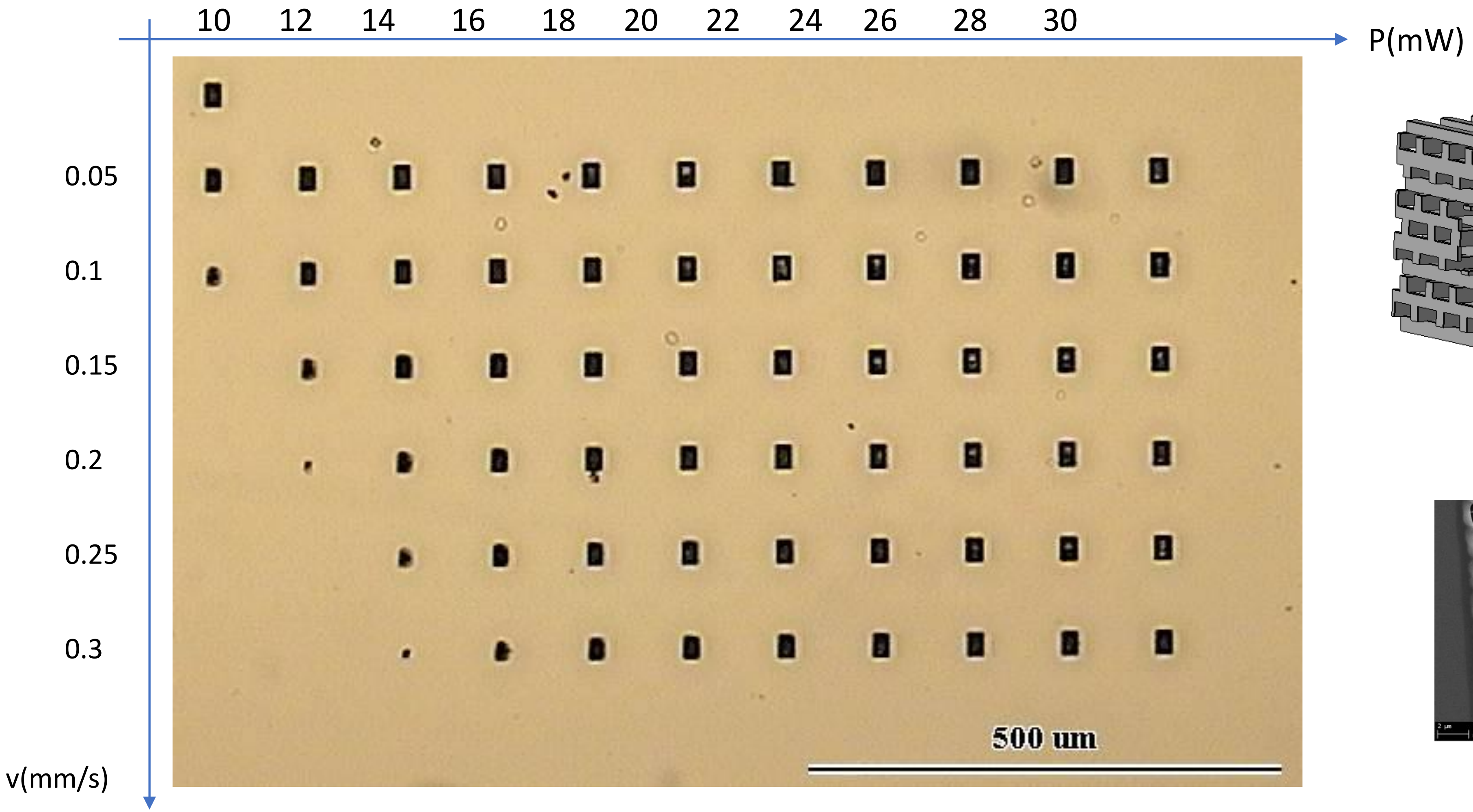


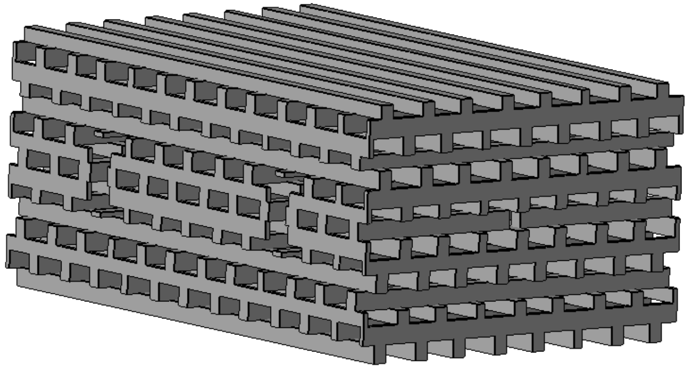
- C. McGuinness, R.L. Byer, E. Colby, B.M. Cowan, R.J. England, et al., "**Woodpile structure fabrication for photonic crystal laser acceleration**", *AIP Conf. Proc. 1086 (2009) 1, 544-549,* DOI: 10.1063/1.3080965;
- I. Sakellari, E. Kabouraki, D. Gray, C. Fotakis, A. Pikulin, N. Bityurin, M. Vamvakaki, M. Farsari, "High-resolution 3D woodpile structures by direct fs laser writing," Proc. SPIE 8456, Nanophotonic Materials IX, 84560E (15 October 2012); https://doi.org/10.1117/12.930155.

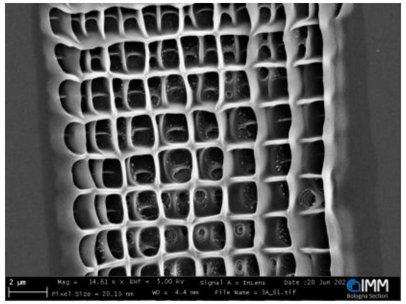
INFN-BOLOGNA
(CNR IMM-Bologna e PoliTO - Chi-Lab)

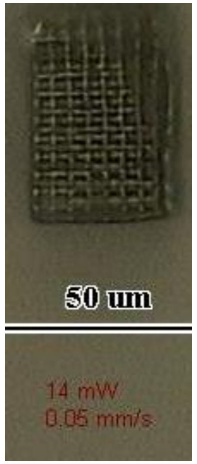
TPP test pattern: a matrix with many woodpile structures (5 μm)
ORMOCOMP / glass

AIM: determine the best printing parameters by varying laser power and velocity







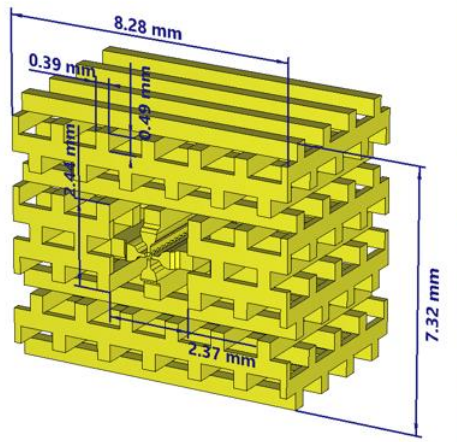


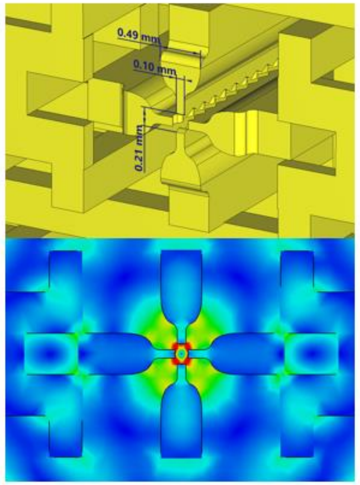
Conclusion and perspectives

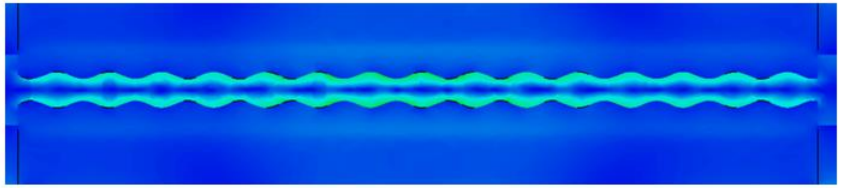
- The design of compact dielectric structures, based on PhCs, for future DLAs setups, has been presented.
- These devices allow co-propagation of the acceleranting wave and the beam.
- Improvements: energy gain efficiency and structure compactness.
- $E_0 \approx 1.6$ GV/m @ $\lambda = 5$ µm with 500 W into the accelerating waveguide (woodpile structure).
- **MICRON** (**MI**niaturised a**C**cele**R**at**O**rs **N**etwork): INFN 5th Nat. Committee project. Ongoing.

➢ **Next step: 5000 nm prototype realization through nanoscale techniques.**

➢ **Next step: numerical study of DLA structures for low-β (0.05 to 0.2) particle acceleration (protons).**







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

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G. Della Valle (PoliMi)