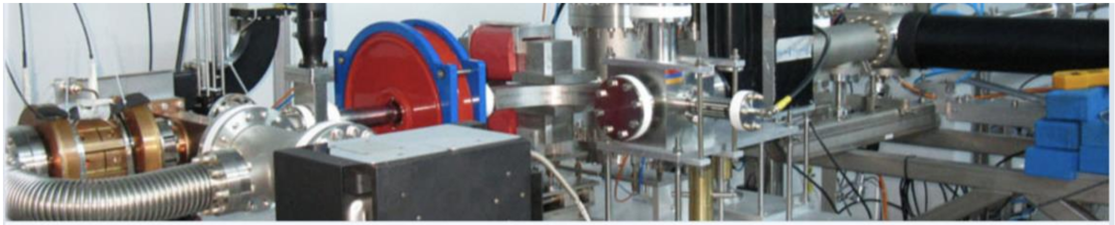
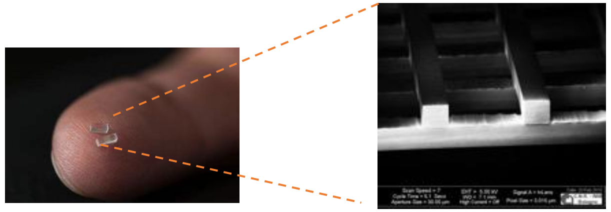


Ultrafast Beams and Applications 04-08 July 2022, CANDLE, Armenia

Copropagating schemes for Dielectric Laser Accelerators

G. Torrisi[1], G. S. Mauro[1], A. Bacci[2], D. Mascali[1], A. F. Usmani[1]
A. Locatelli[2,3], C. De Angelis[2,3]
G. Della Valle[4],
R. Rizzoli[5], V. Bertana[6], S. Marasso[6]
and G. Sorbello[7,1]



[1]Istituto Nazionale di Fisica Nucleare–Laboratori Nazionali del Sud (INFN-LNS), Via S. Sofia 62, 95123 Catania, Italy
[2]Istituto Nazionale di Fisica Nucleare–Sezione di Milano, Via Celoria 16, 20133 Milan, Italy
[3]Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia, Via Branze 38, 25123 Brescia, Italy
[4]Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy
[5]Consiglio Nazionale delle Ricerche Istituto per la Microelettronica e Microsistemi Unità di Bologna, Via Gobetti 101, Bologna,Italy,40129
[6]DISAT - Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy
[7]Dipartimento di Ingegneria Elettrica, Elettronica e Informatica, Università degli Studi di Catania, Viale Andrea Doria 6, 95125 Catania, Italy

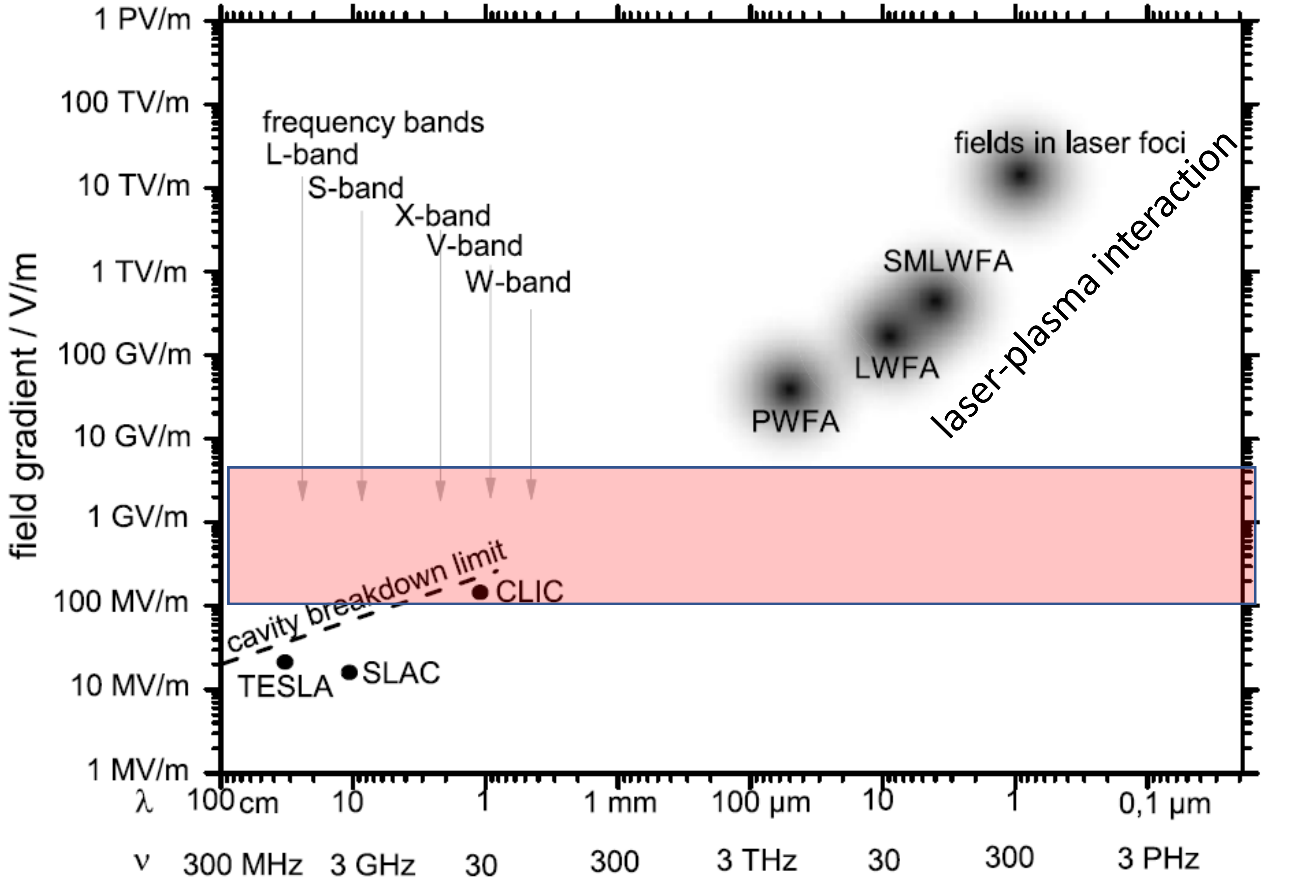
DLA Motivations

High <u>accelerating</u> gradients enable compact/miniaturized particle accelerators

TARGET

Accelerating Gradient: <u>~ 500 MV/m - 2 GV/m</u>

schematic overview of the accelerating gradient for different types of accelerators



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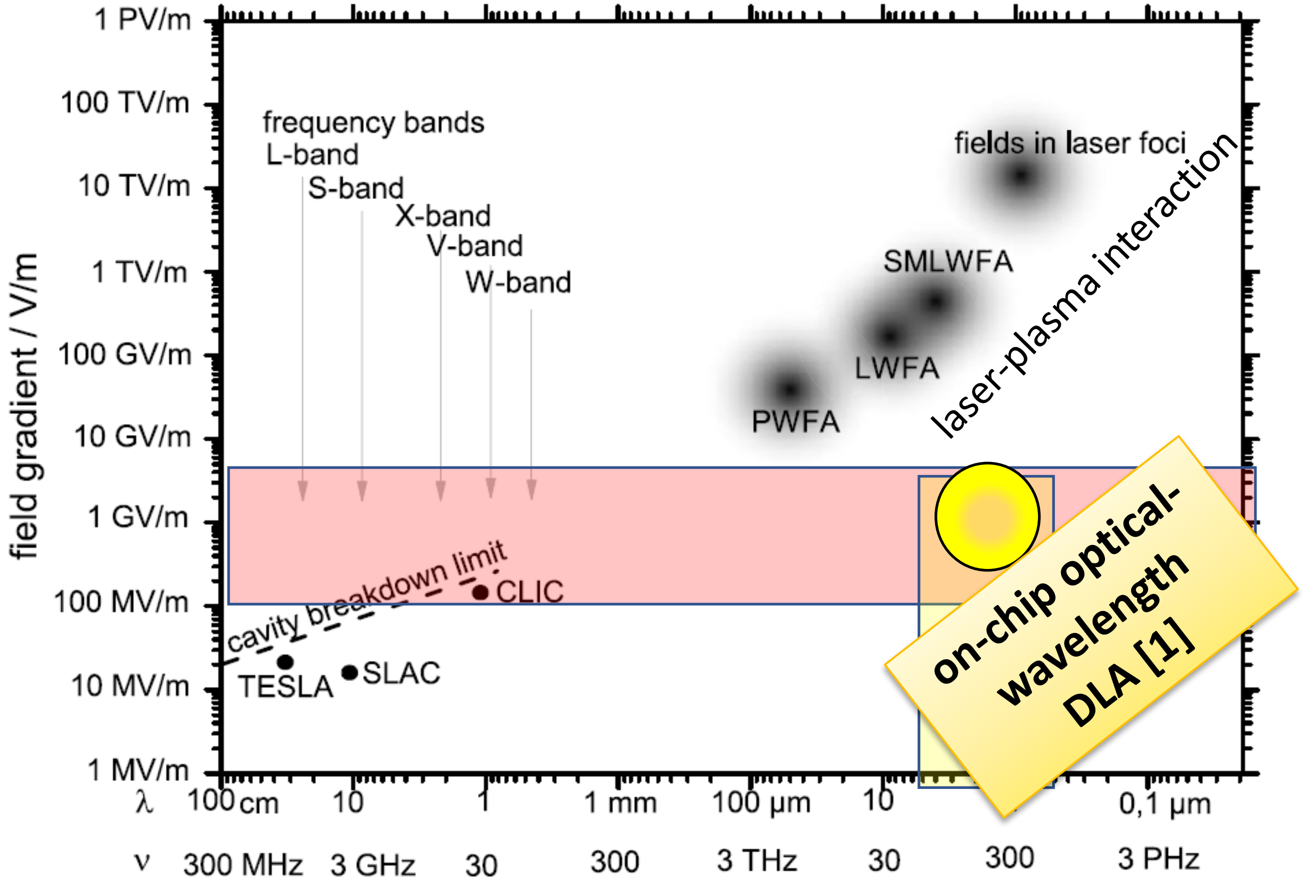

[1] R. Joel England *et al., "*Dielectric laser accelerators" Rev. Mod. Phys. **86**, 1337 –23 December 2014

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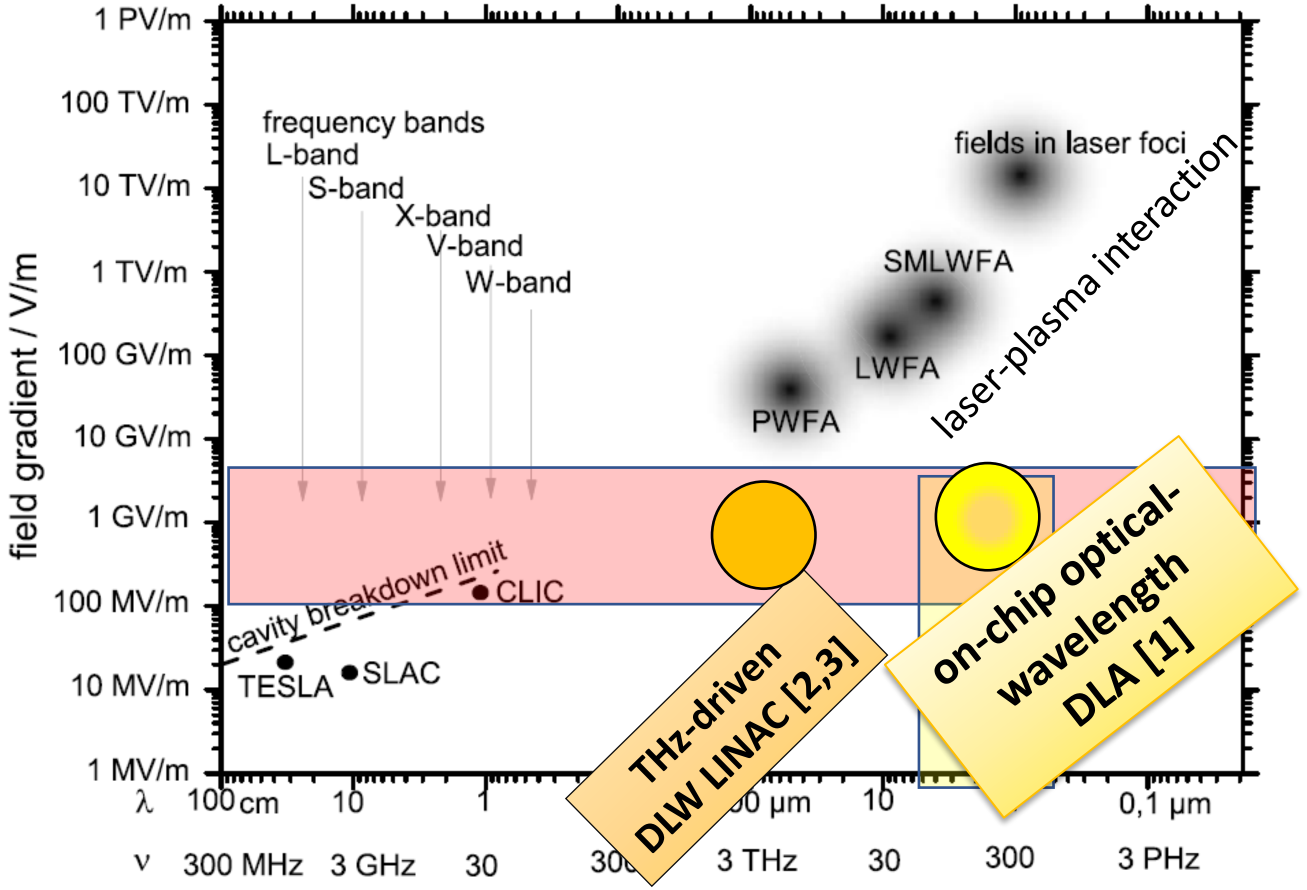

[1] R. Joel England *et al.,* Rev. Mod. Phys. **86**, 1337-2014
[2] E. Nanni, *et al., Nat Commun* **6,** 8486 (2015).
[3] F. Lemery, *et al.” Commun Phys* **3,** 150 (2020).

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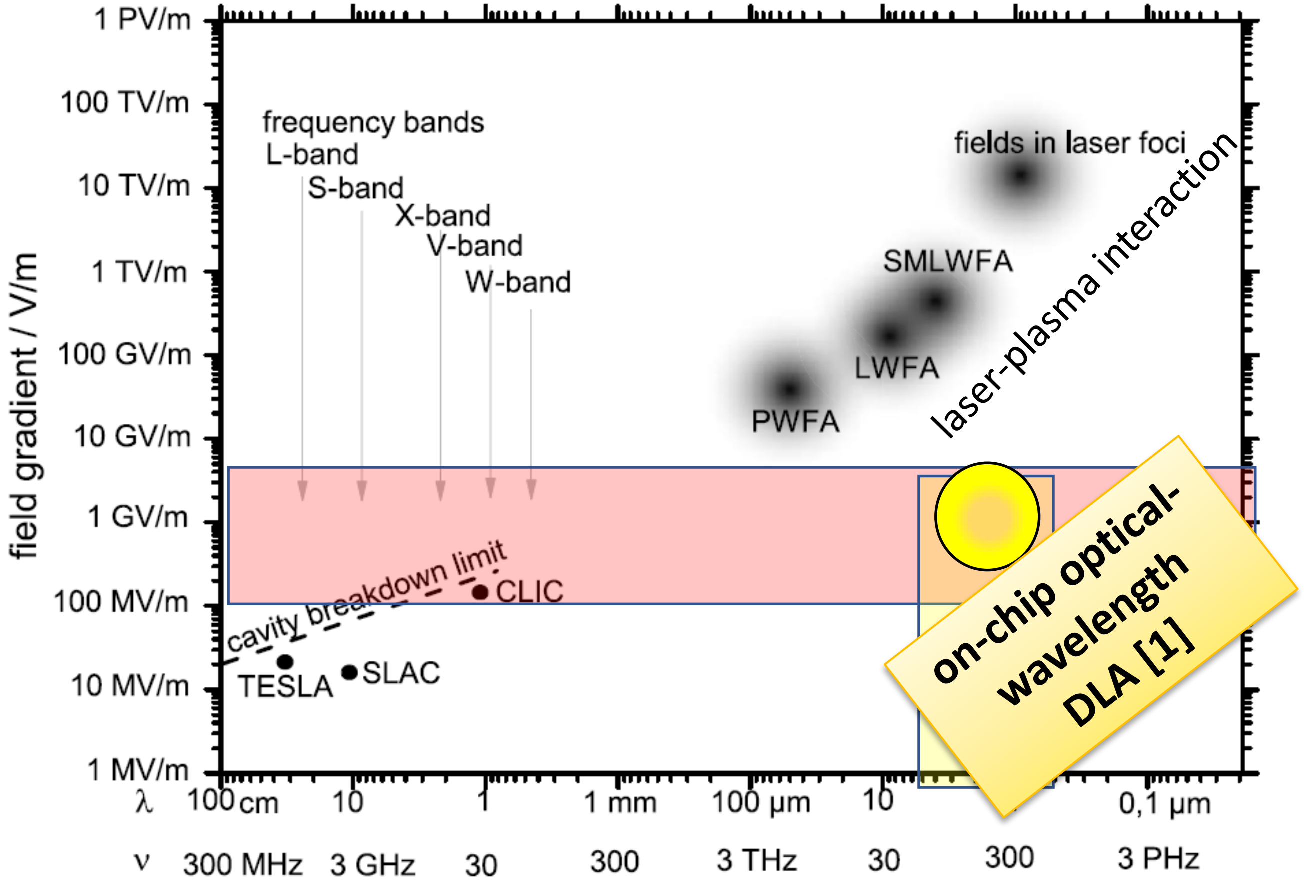
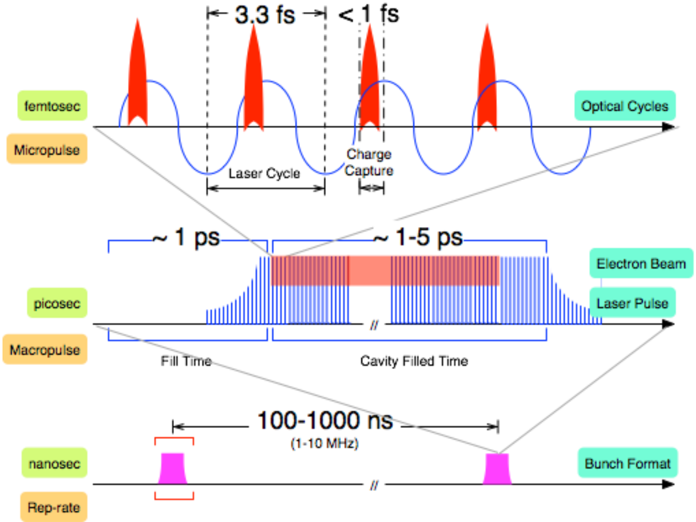


[1] R. Joel England *et al.*, "Dielectric laser accelerators" Rev. Mod. Phys. **86**, 1337 –23 December 2014

Fundamental DLA properties

- DLAs uses an **ultrafast** IR laser



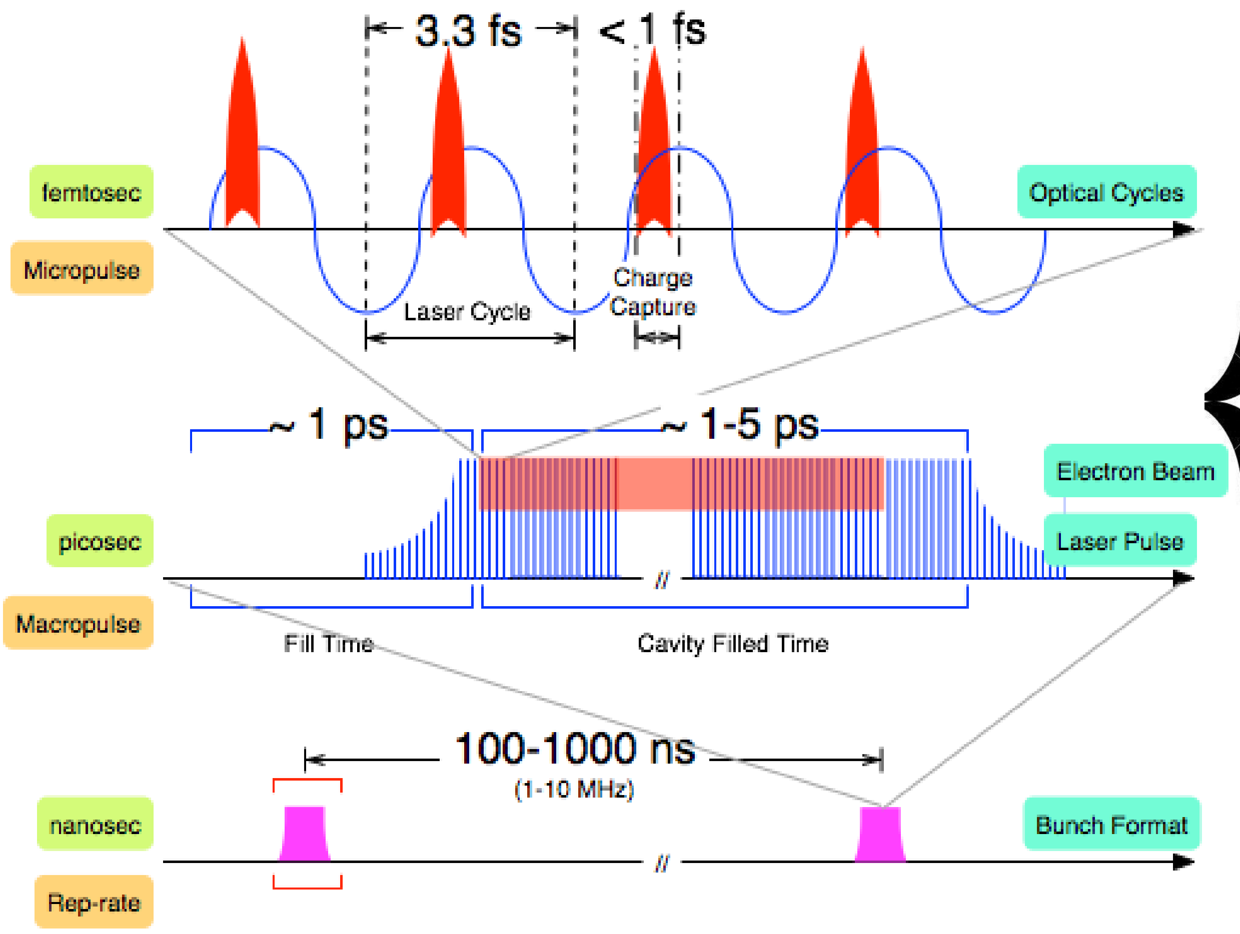
- infrared lasers @ **1<λ<10µm**
- typical laser **pulse lenghts** **0.1-1 ps**
- peak surface **E-field** **~ GV/m**
- **microjoule laser** **(~ kW [on ps])**
- **high repetition rate** **~ MHz**

- Bunches of **subfemtosecond** duration (**low-charge bunches at high repetition rate**)

- **relevant apertures less than the wavelength (typically 0.3 to 0.8 λ)**
- λ=800 nm, optical cycle → 2.7 fs , λ=2 µm, optical cycle → 6.7 fs
- bunch format **attosecond** (10^{-18} s) **bunch lengths**
- Typical optimal microbunch charges in the range of **1–10 fC**
- particle-beam pulse format (low-charge bunches at high repetition rate)

[Journal of Applied Physics 124, 023104 (2018); doi: 10.1063/1.5032(
[Appl. Phys. Lett. 116, 161106 (2020); doi: 10.1063/5.0003575]

Fundamental accelerator properties



One of the most promising applications is compact electron sources **for ultrafast science and electron diffraction.**

Trains of ultrafast and ultrabright electron bunches with subfemtosecond intrinsic bunch structure could allow resolution of electronic processes in both spatial and temporal domains, thereby enabling **new tools for imaging light– matter interactions and for experiments in quantum electrodynamics.**

[“Recent Results in Dielectric Laser Acceleration of Electrons Physics and Applications of High Brightness Beams”, Cuba, 2016 R. Joel England]

DLA APPLICATIONS and **potential areas of scientific interest**

APPLICATION	FIELD	TIME-SCALE
Compton X-ray Source	Medical	Mid
Catheterized Electron Source	Medical	Mid
Proton/Hadron Therapy	Medical	Long
Low-power EUV for inspection	Medical	Long
Linear Collider	HEP	Long
Micro-beams for radiobiology	Science	Near
UED/UEM Source	Science	Near
Compact XFEL	Science	Long
Multi-Axis Tomography	Science	Long
Colliding Beam Fusion		

- Nano- or micro-beam for radiobiology and radiation chemistry
- Ultrafast electron diffraction, X-ray pulses at sub-fs time scales
- ultrafast science (molecular movies, atomic physics).
- Compact, portable scanners for security (Nuclear Fluorescence), phase contrast imaging and medicine.

***Copropagating schemes* for Dielectric Laser Accelerators**

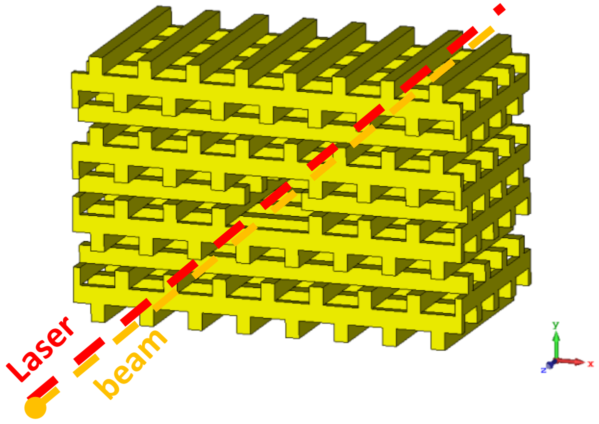
Copropagating schemes for Dielectric Laser Accelerators

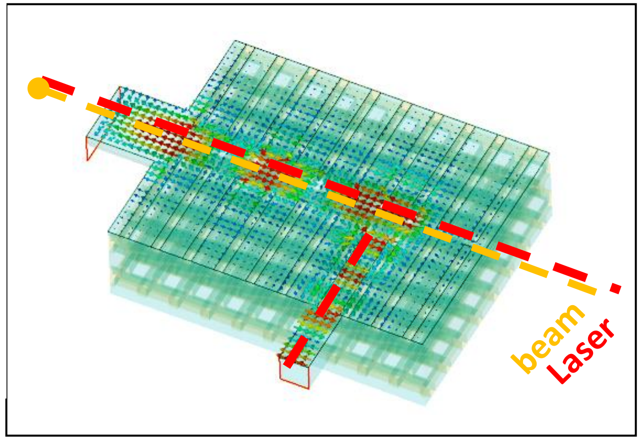
What we mean for ***Copropagating?***

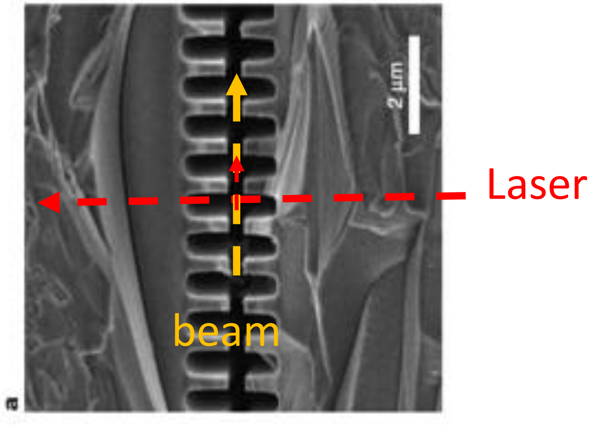
***Copropagating* schemes**

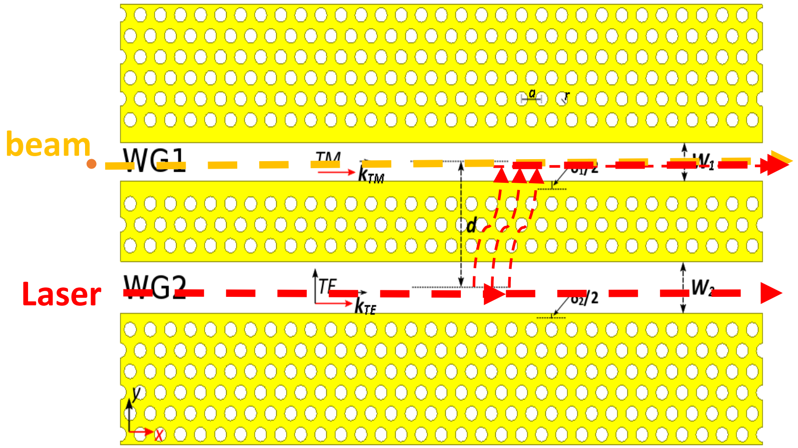
vs

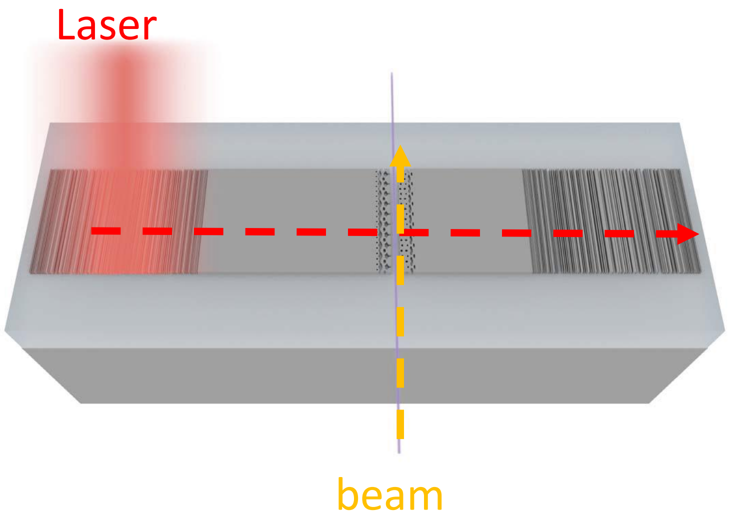
Cross-propagating schemes







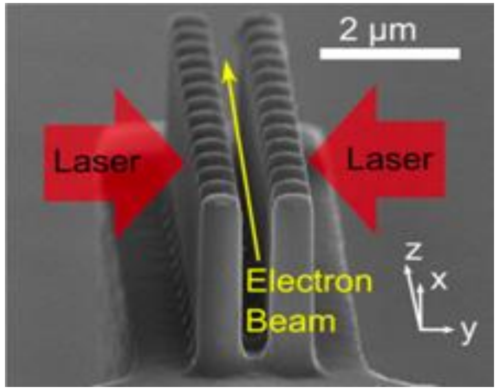


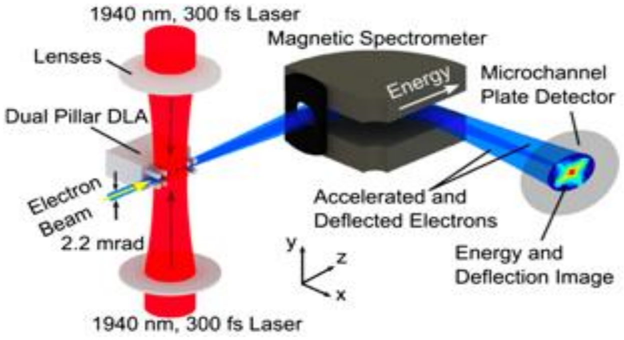


[New Acceleration Concepts.
"Dielectric Laser Acceleration", Joel England (SLAC)
Snowmass AF6 Meeting Sept 23, 2020]

Cross-propagating schemes

"transverse-illuminated" *Phase Reset Device*





↓

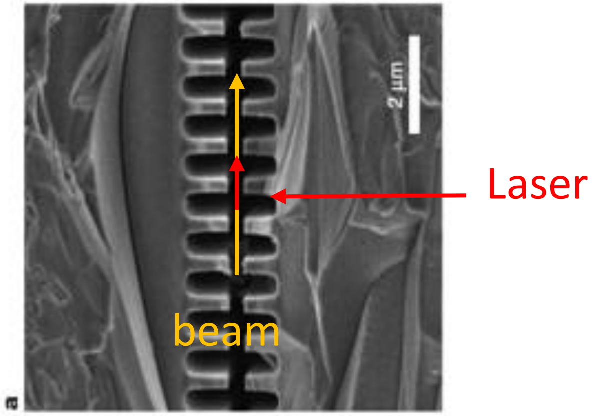
short interaction region
(few μm)

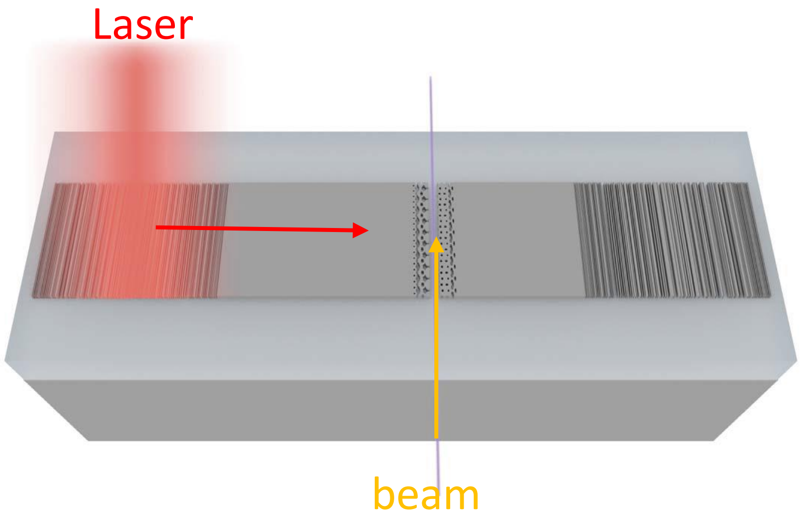
↓

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]

[Rasmus Ischebeck, Uwe Niedermayer with contributions by the ACHIP collaboration "***Dielectric Laser Accelerators***," *Townhall Meeting High Gradient Acceleration Plasma/Laser* 30-3-2021]

***Cross-propagating** schemes*

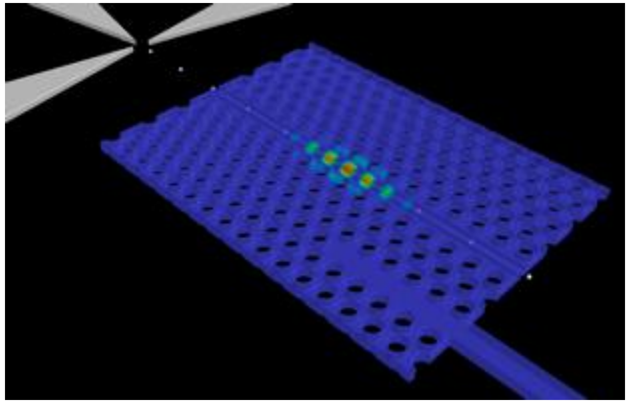
Primary Challenges for a DLA Collider

- Small beam apertures
  - Wakes
  - Halo
  - **Long-distance transport**
- Need high-rep rate e^+ and e^- sources
- Current funding for this area of research is not directly focused on HEP applications

A Collider is much more than Accelerating Structures

- Focusing and beam transport
- Longitudinal Phase Space Control
- **Power delivery**
- Instrumentation and feedbacks
- Halo control

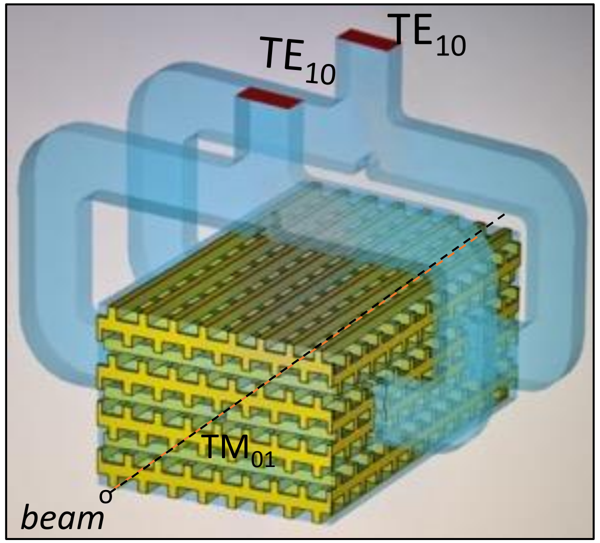
Photonic Crystal (PhC)-based Dielectric Laser Accelerator (DLA)



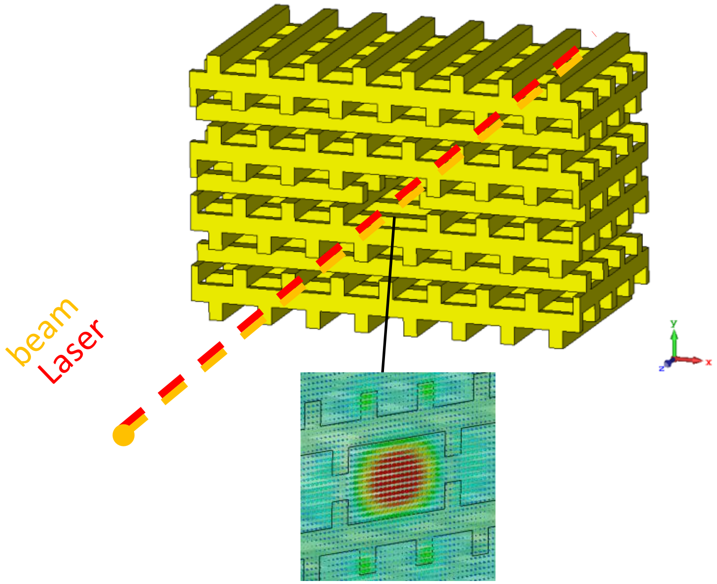
*DLA **high-Q photonic-crystal cavity***
[courtesy of C2N]

<u>Copropagating</u> schemes

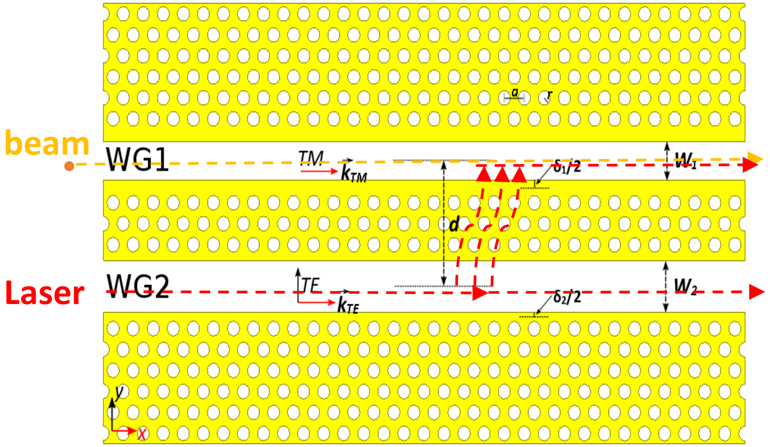
- **Hollow-core waveguides** for <u>high power handling</u>
- **Collinear** <u>co-propagating</u> laser and particle beam
- <u>**High interaction impedance** Z_c</u> and accelerating gradient
- <u>**Continuous wave** (CW)</u> laser operation (1-5 µm)



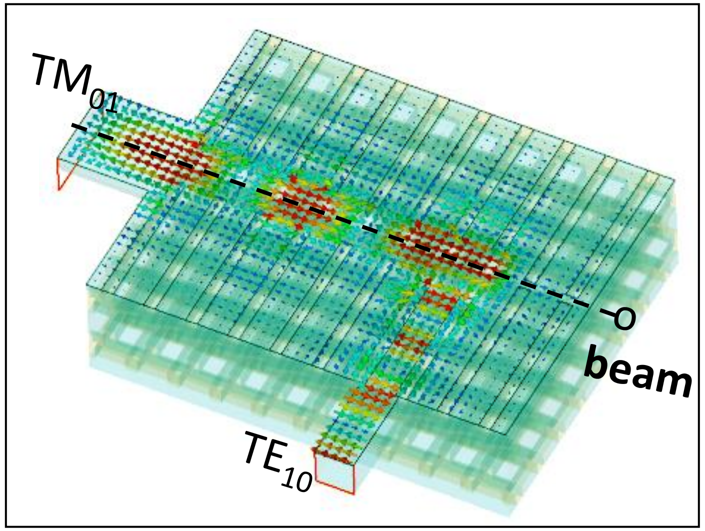
*3D Silicon **Woodpile mode launcher***



***2D** longitudinal Photonic Crystal*
Directional Coupler



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



3D woodpile hollow-core mode converter

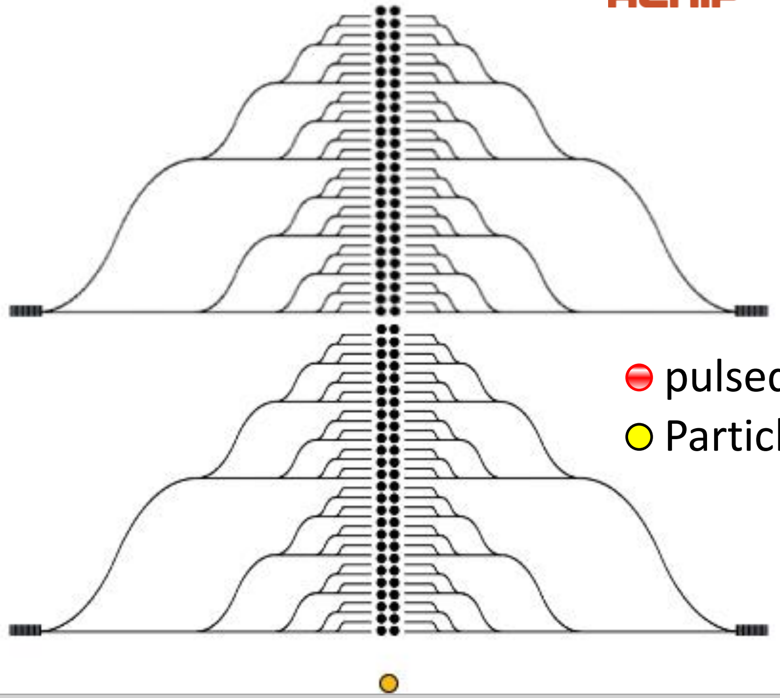
[G. S. Mauro et al., " in IEEE MTT, 68, 5, 1621-26, 2020]

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

Cross-propagating schemes vs **Copropagating schemes**

side-pumped configurations Power Delivery

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

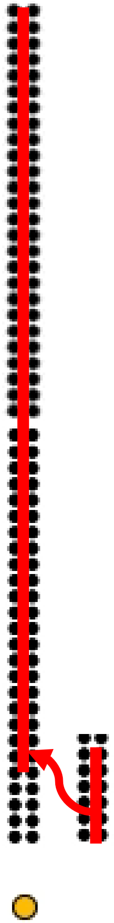


pulsed Laser
Particle

- require a complex **2D feeding** network with a **large footprint proportional to L^2**
- the input facet becomes a bottleneck for damage and nonlinear effects
- Dispersion Management is needed

CW collinear hollow-core scheme Power Delivery

CW Laser
Particle



- **quasi-1D topology,** based on hollow-core waveguides
- reaching a final energy **scales linearly with the structure length L**
- hollow-core coupling structure prevents non-liner effect

CW DRAWBACKS:
Power Losses
Efficiency

Copropagating <u>schemes</u> for Dielectric Laser Accelerators

What we mean for ***<u>schemes?</u>***

We require

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

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

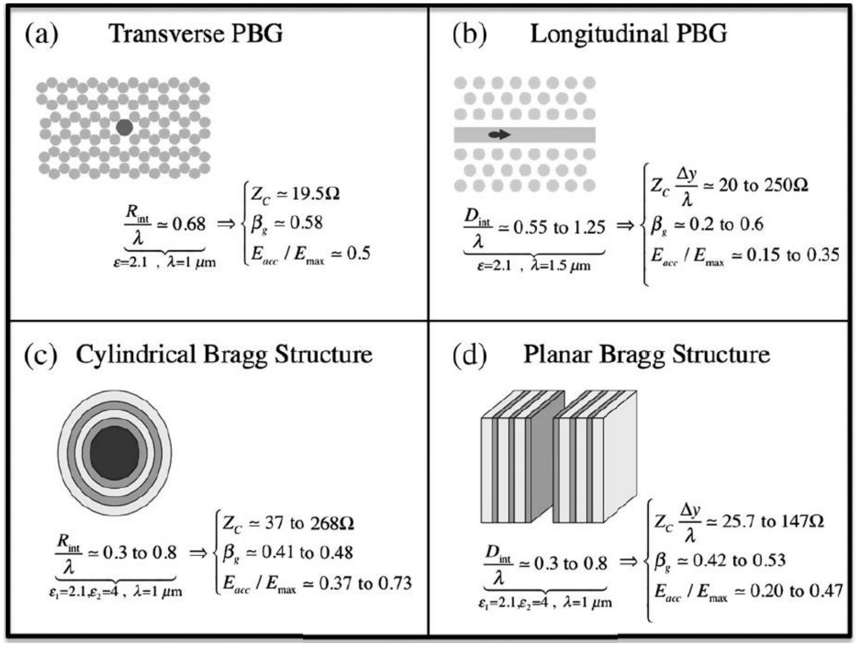
An important feature common to all dielectric acceleration structures stems from the fact that they are not enclosed by conductive boundaries. As such, high order modes (higher frequency) which may disrupt the beam are not confined as in metallic microwave structures but rather they leak out

Copropagating schemes for Dielectric Laser Accelerators

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

R.J. England et al., *Dielectric laser accelerators*, Rev. Mod. Phys., 2014

- Photonic Crystal (PC) DLAs geometries:
  - a) Transverse PC.
  - b) Longitudinal PC.
  - c) Planar Bragg structure.
  - d) Cylindrical Bragg structure.
- Our goal:
  - Definition of guidelines for design of PC accelerating waveguides
  - Fabrication of prototypes



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 lattice**, by removing or altering one element of the structure, **a guided mode can be trapped inside the structure.**
- For DLA use, defect is typically a linear hollow channel:

a) accelerating mode with longitudinal electric field along the axis of the particle trajectory;

b) phase velocity equal to the particle velocity.

- Infinite number of geometries that can form an EBG structure.
- We are especially interested in those **geometries that promotes the exixtence of a complete 3D frequency band-gap.**

Copropagating schemes for Dielectric Laser Accelerators

Copropagating schemes for Dielectric Laser Accelerators

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

1) Slotted waveguide @ 5 μm

2) 2D photonic crystal waveguide

3) Woodpile @ 5 μm

Copropagating schemes for Dielectric Laser Accelerators

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

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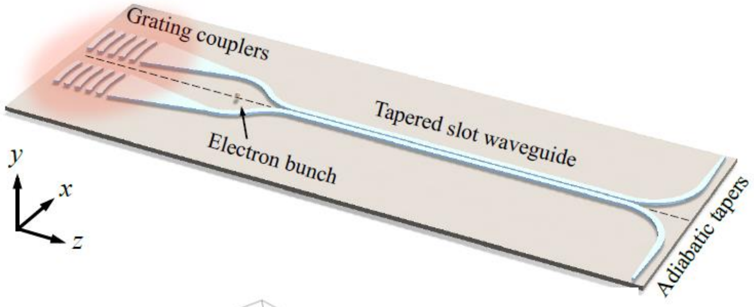
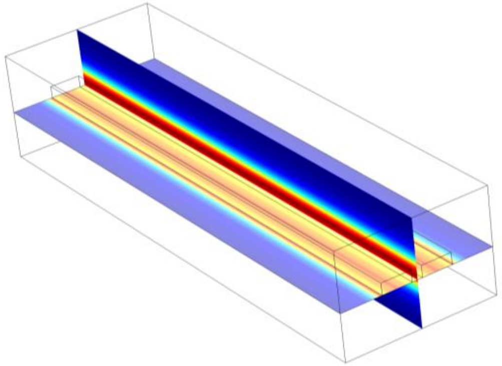
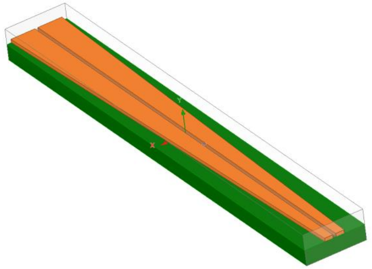
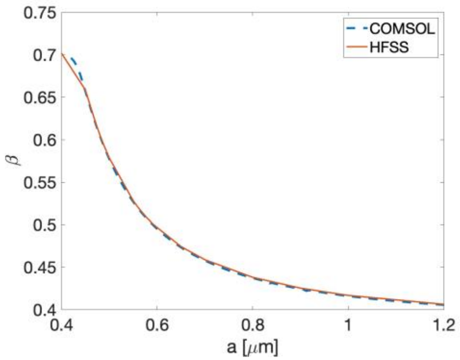
$[0.4 < \beta < 0.75,\ Zc$=1.5 kΩ]

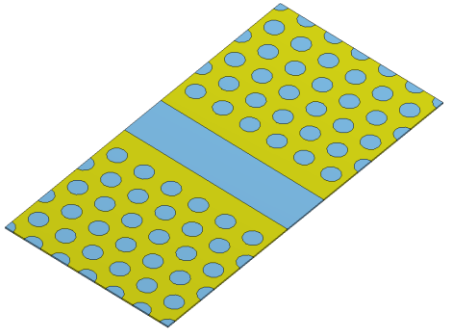


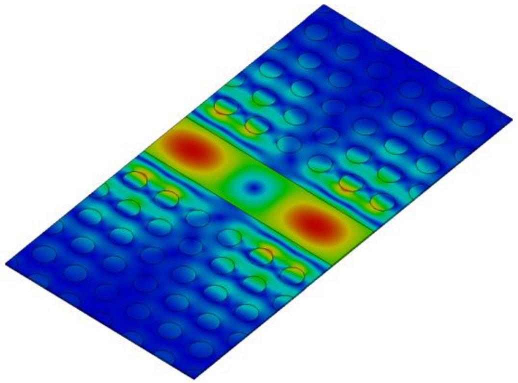


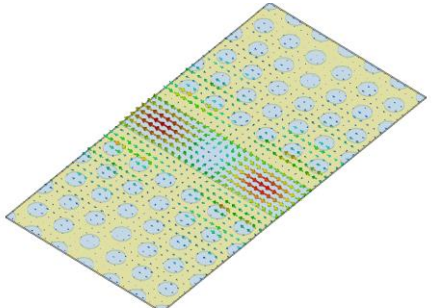




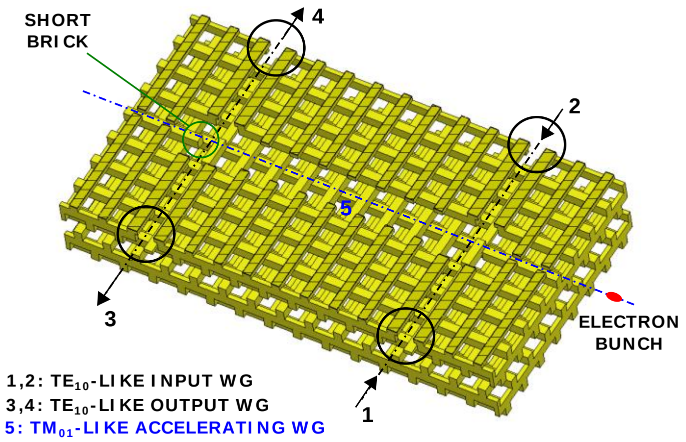
2) 2D photonic crystal waveguide
$[\beta = 1]$





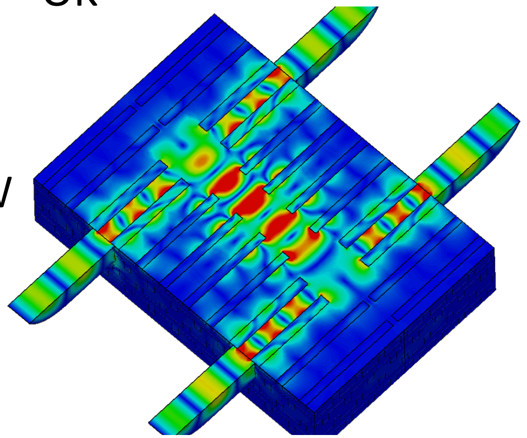


3) Woodpile @ 5 μm
$[\beta = 1, Z_c$ = 11.4 kΩ]



OK

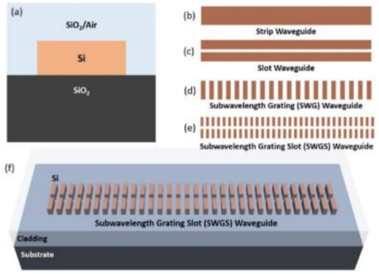
~ 1 GV/m
@ P_inj=1 kW

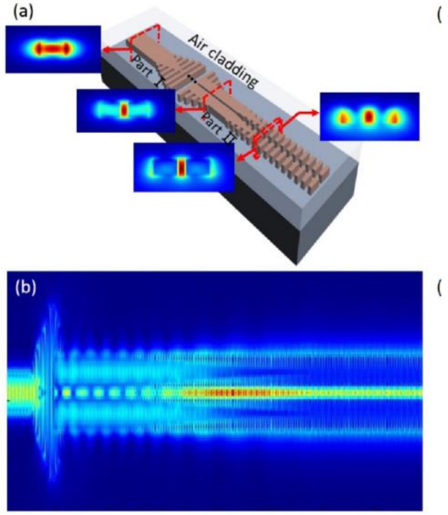


Copropagating schemes for Dielectric Laser Accelerators

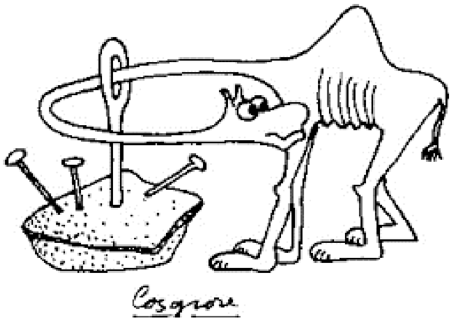
A bit out of ***schemes….***

Subwavelength grating slot (SWGS) waveguide on silicon platform [low β]



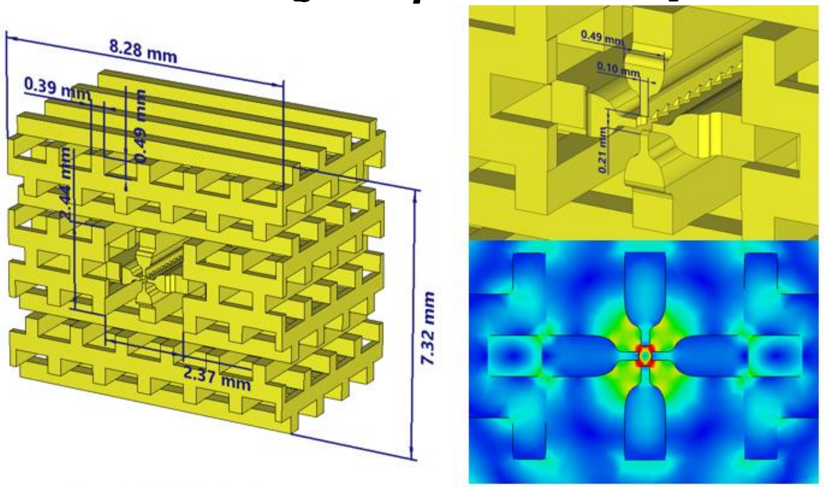


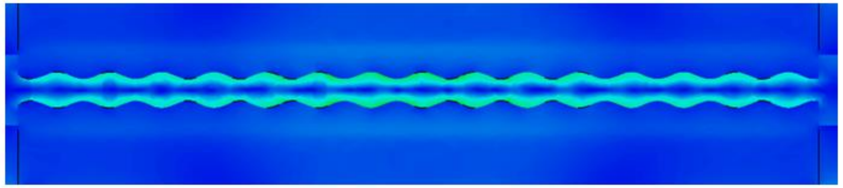
Proton-DLA?



Dielectric Photonic Crystal woodpile-based RFQ

[from β 0.05 to 0.2]



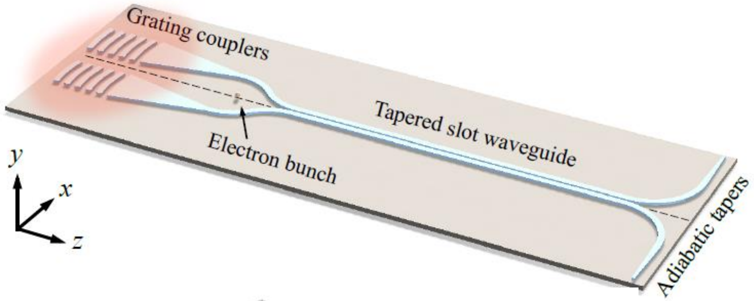


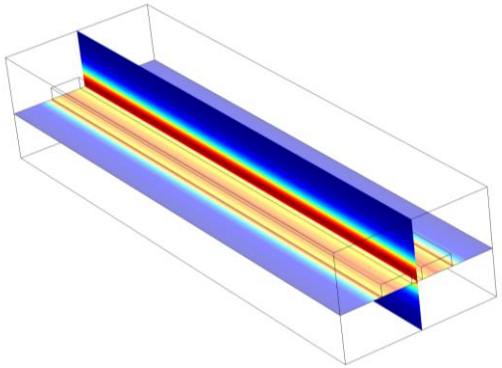
Patent pending
Metodo per progettare una struttura accelerante dielettrica che supporta un modo TE_{210}-like perturbato (Ita. Patent pending n. 102021000021158)
By: G. S. Mauro, G. Torrisi, D. Mascali, G. Sorbello, S. Gammino (INFN-LNS),
G. Della Valle (PoliMi)

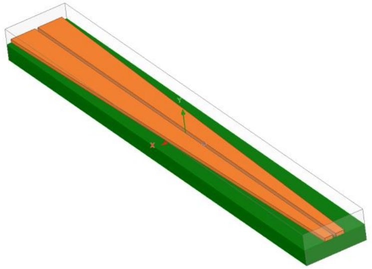
Copropagating schemes for Dielectric Laser Accelerators

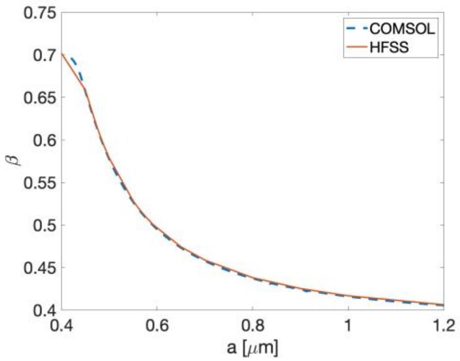
What we mean for ***schemes?***

1) Slotted waveguide @ 5 μm
$[0.4 < \beta < 0.75,\ Zc$=1.5 kΩ]









2) 2D photonic crystal waveguide
$[\beta = 1]$

3) Woodpile @ 5 μm
$[\beta = 1, Z_c$ = *11.4* kΩ]

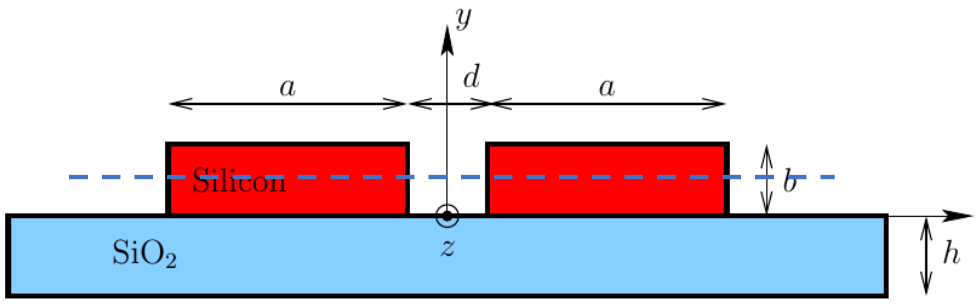
OK

~ 1 GV/m
@ P_inj=1 kW

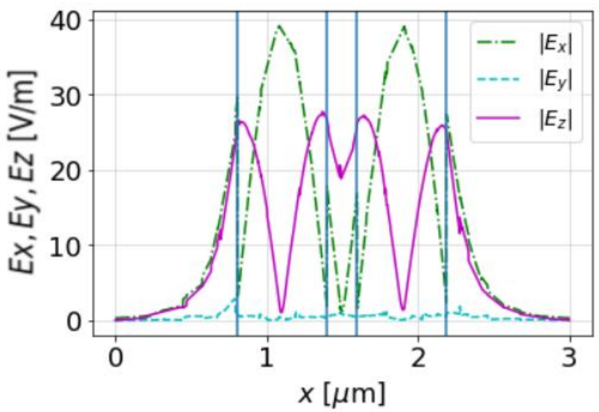
1) *Slotted waveguide*

SLOTTED WAVEGUIDE

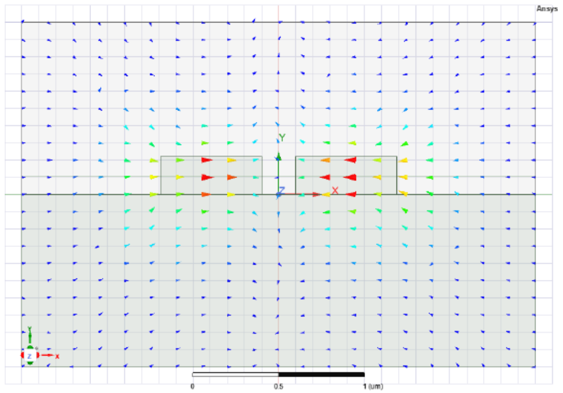
Geometry



"Accelerating" mode-Electric field
$|E_i|$ components
along dashed-line
(odd symmetry)



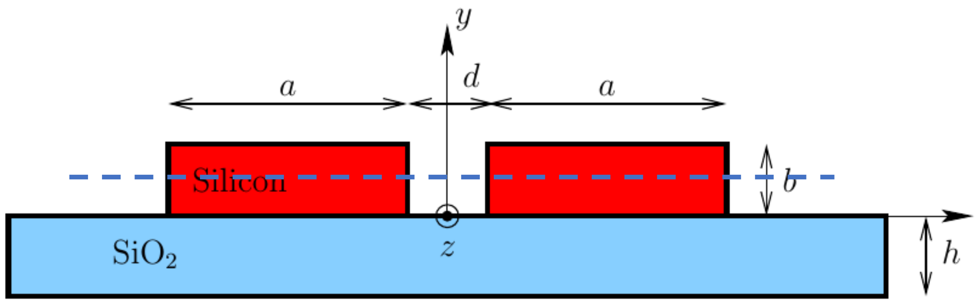
***"Accelerating"** mode-Electric field*
arrow-plot on the excitation input port



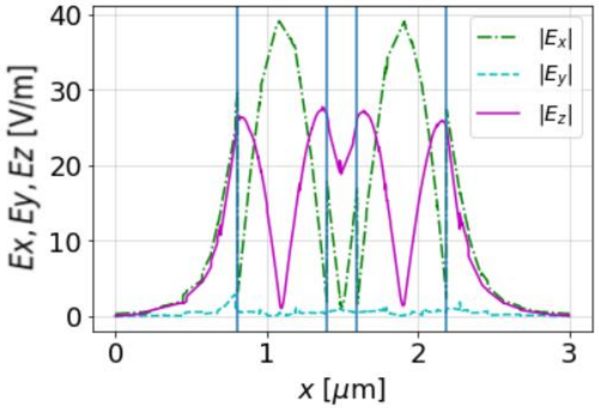
1) Slotted waveguide

SLOTTED WAVEGUIDE

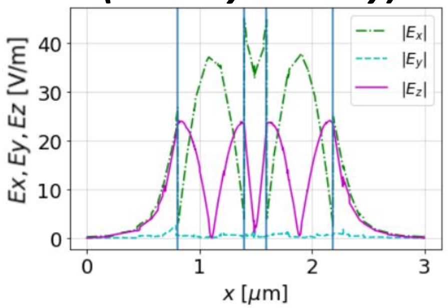
Geometry



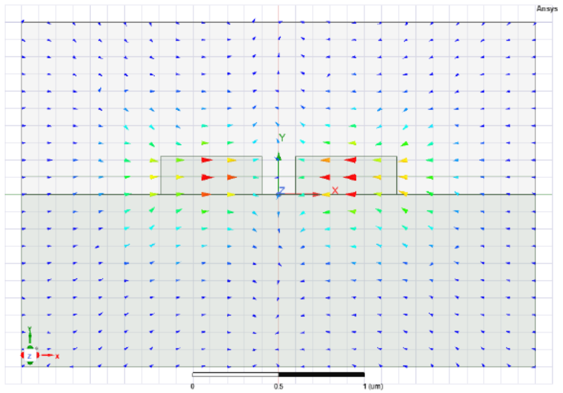
"Accelerating" mode-Electric field
$|E_i|$ components
along dashed-line
(odd symmetry)



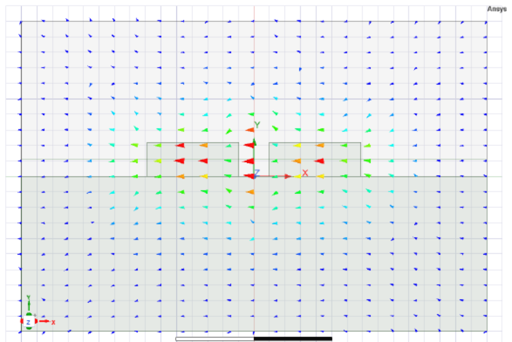
"Fundamental" mode-Electric field
(even symmetry)



<u>"Accelerating"</u> mode-Electric field
arrow-plot on the excitation input port



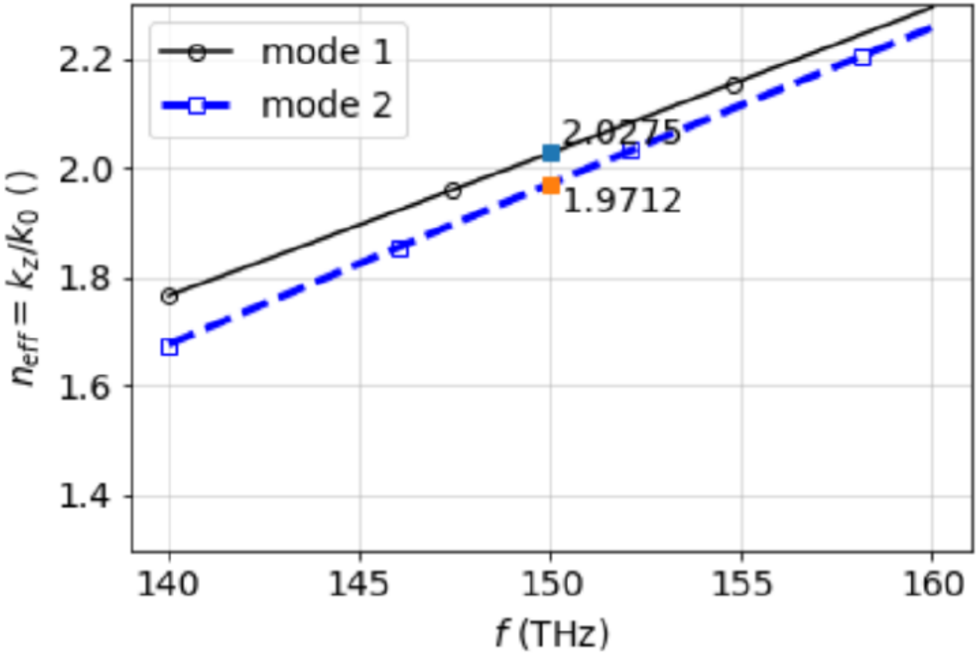
"Fundamental" mode-Electric field
arrow-plot on the excitation input port



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**

Slotted waveguide Effective index computation

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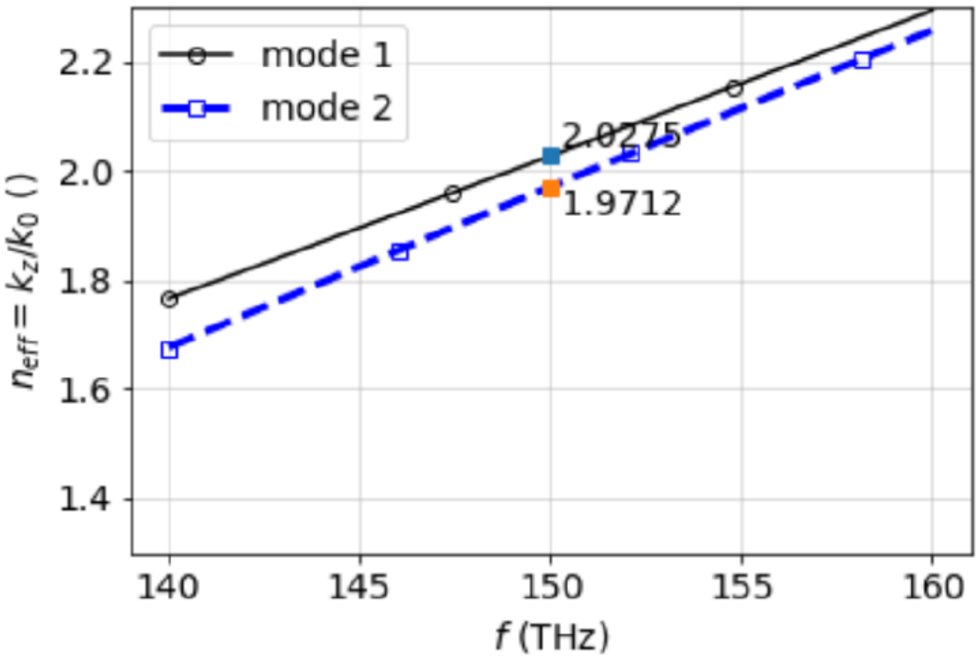
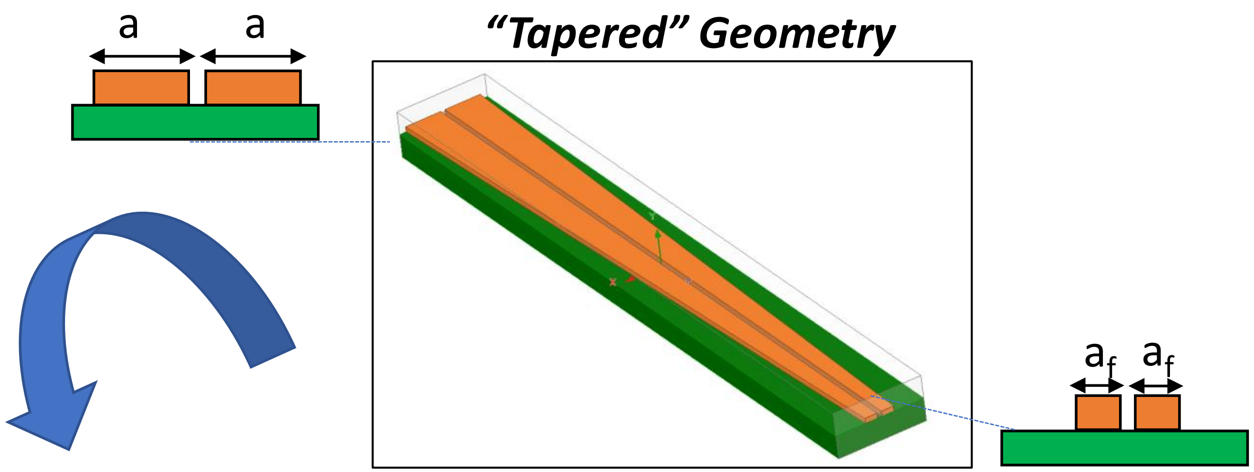


f=150 THz

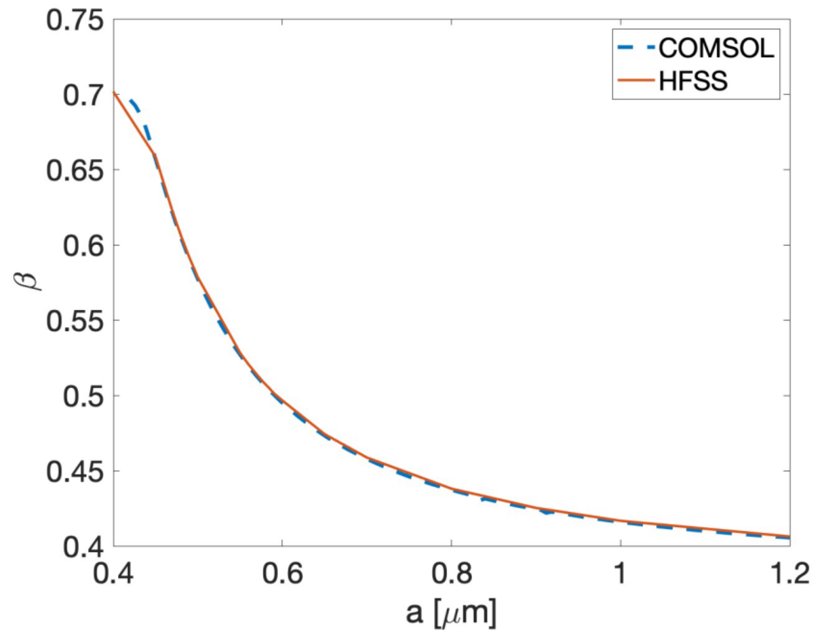
n_{eff}=1.9712

$\boldsymbol{\beta = 0.5}$

Tapered slot waveguide for sub-relativistic electrons



β variation due to the slot width size a tapering



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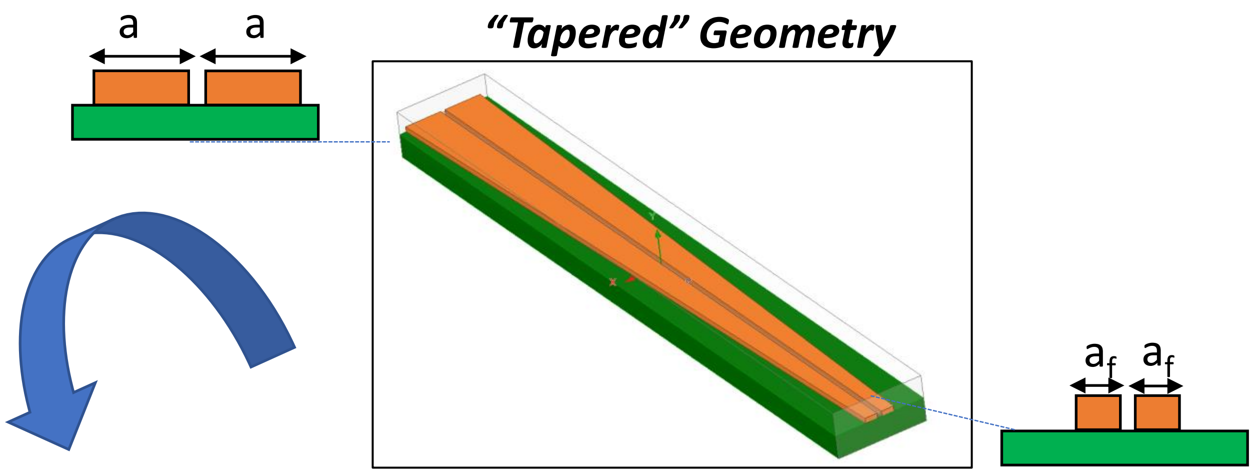

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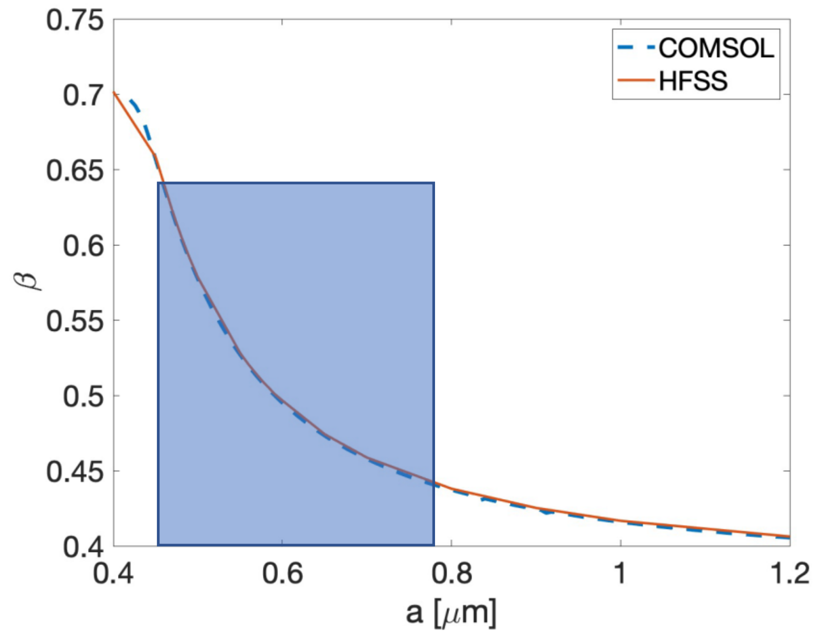

Slotted waveguide
"safe" range
$\mathbf{0.4 < \beta < 0.63}$

a (μm)	β	$E_{\text{total}}(KeV)$
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

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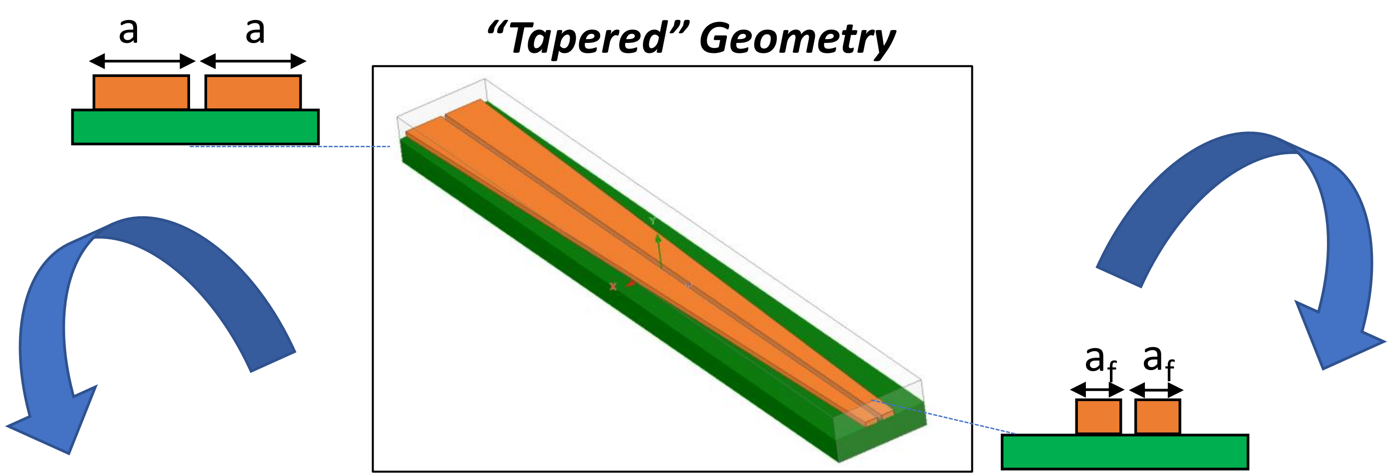

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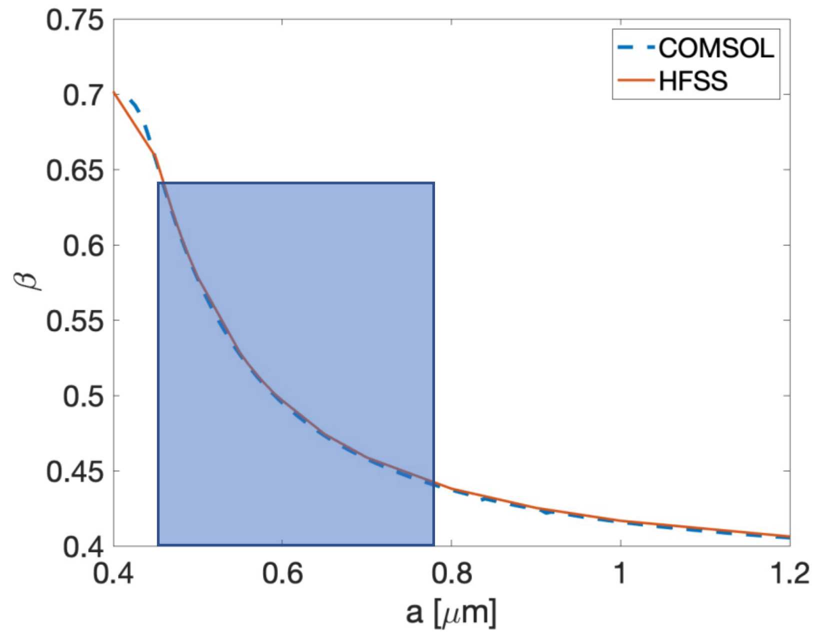

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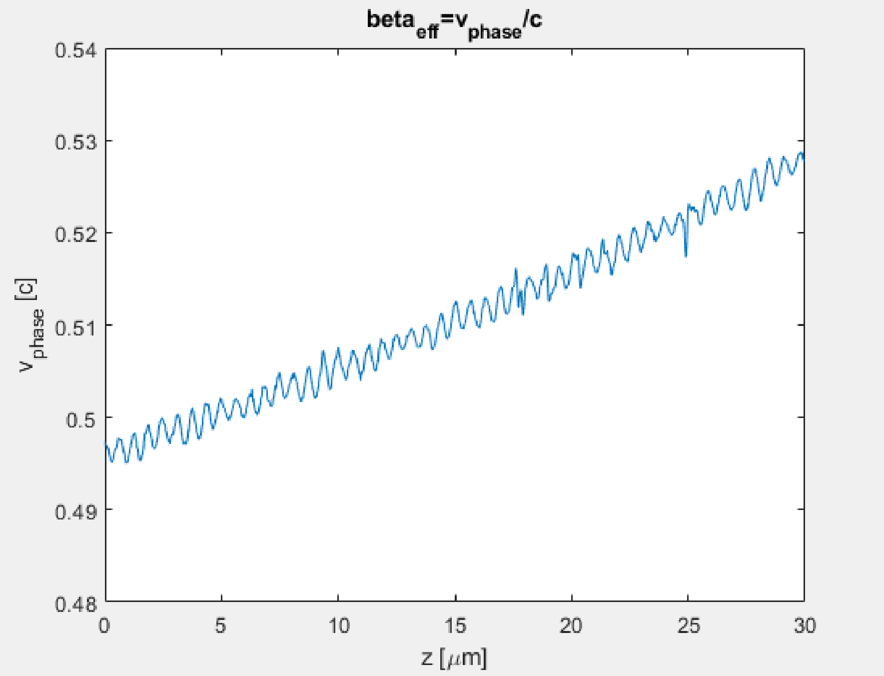
0.80	0.44	58.12

Phase velocity variation along the waveguide



*Copropagating **schemes** for Dielectric Laser Accelerators*

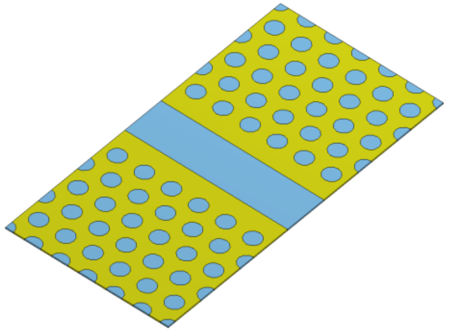
What we mean for ***schemes?***

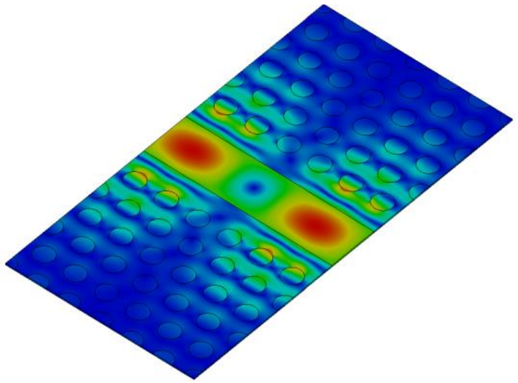
1) Slotted waveguide @ 5 μm

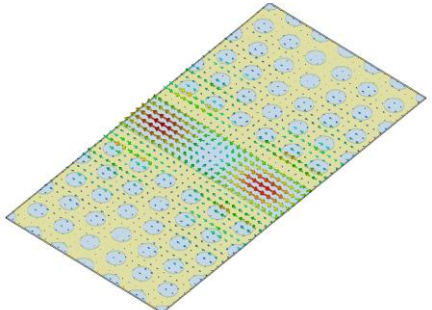
$[0.4 < \beta < 0.75,\ Zc$=1.5 kΩ]

2) 2D photonic crystal waveguide

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







3) Woodpile @ 5 μm

$[\beta = 1, Z_c$ = *11.4* kΩ]

OK

~ 1 GV/m

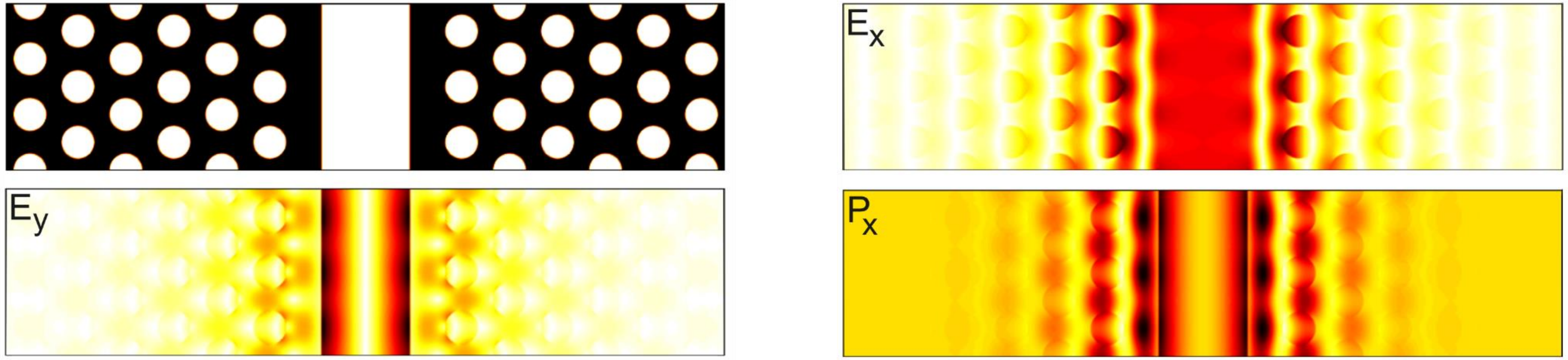
@ P_inj=1 kW

2) 2D photonic crystal waveguide

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

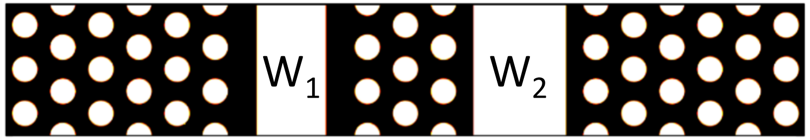
Design of PC accelerating waveguides

- The accelerating mode:
  - It is a <u>surface mode</u>: transverse field E_y and longitudinal Poynting vector P_x are confined at the PC - air interface.
  - The longitudinal field E_x is rather intense and uniform along the air channel where light and particles travel in a synchronous fashion.



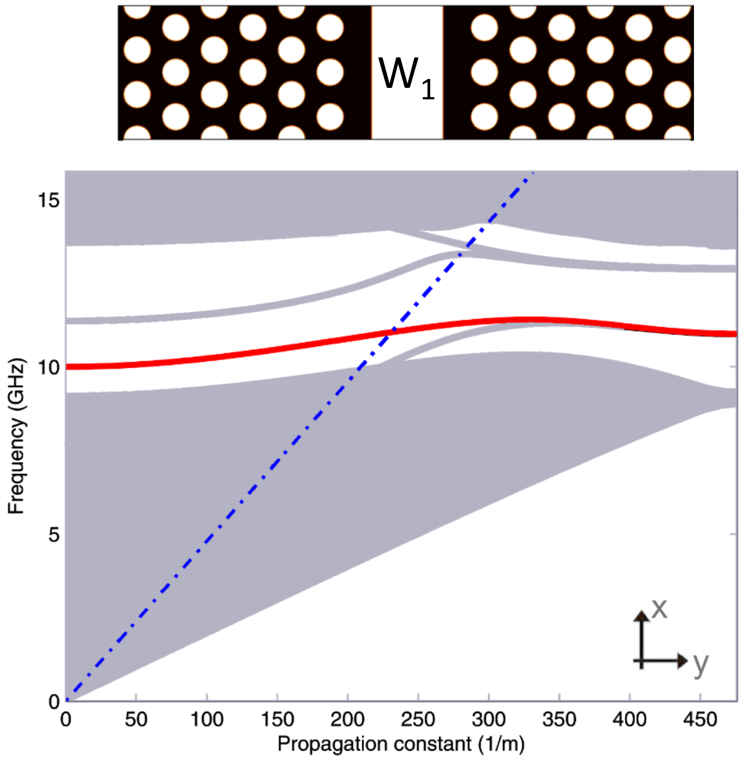
Design of PC input couplers

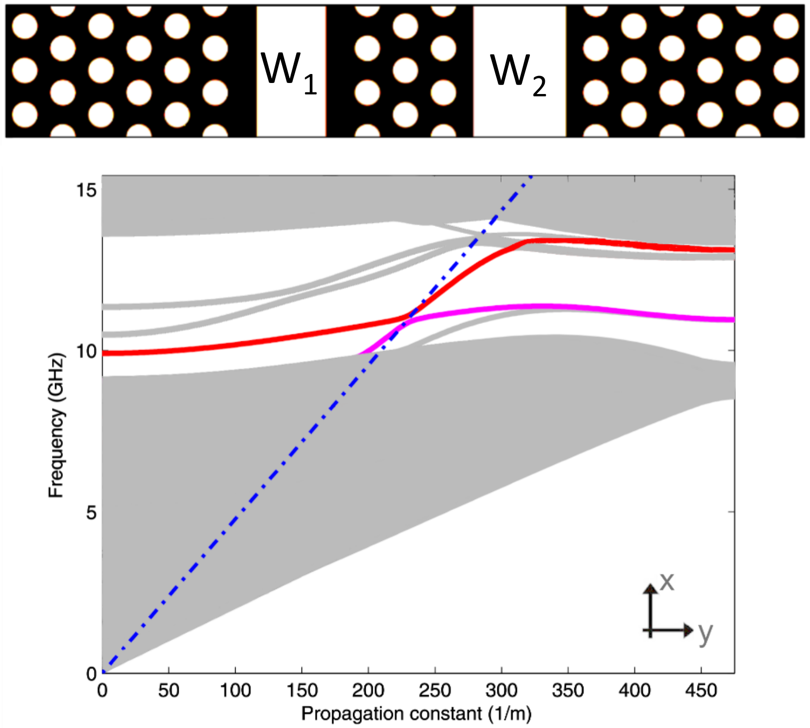
- Efficient coupling with the accelerating waveguide:
  - Not trivial, since the accelerating field has the form of a surface mode.
  - We designed a PC directional coupler to improve coupling efficiency:
    - The first waveguide (width $W_1 = 1.6a$) supports an accelerating mode The second one (width $W_2 = 2.13a$) supports a transverse mode
    - Synchronization of an accelerating and a transverse mode by varying W.
    - When the waveguides couple, efficient energy exchange is possible.



Design of PC input couplers

- Projected band structure:
  - From the single isolated waveguide to the coupled waveguides.

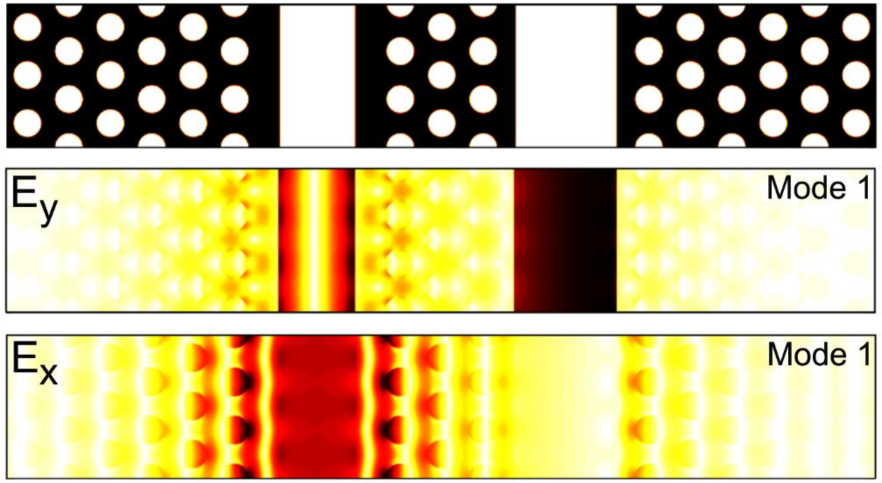


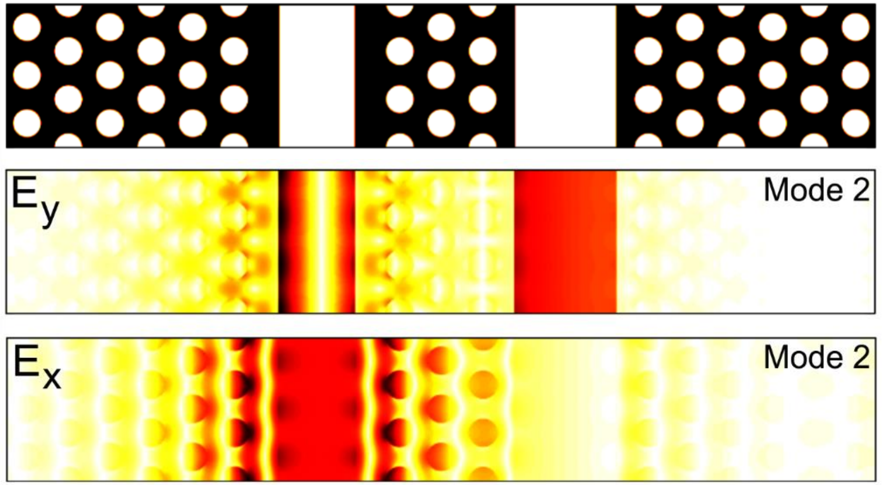


$$L_B = \frac{\pi}{\Delta\beta} = 31.4a$$

Design of PC input couplers

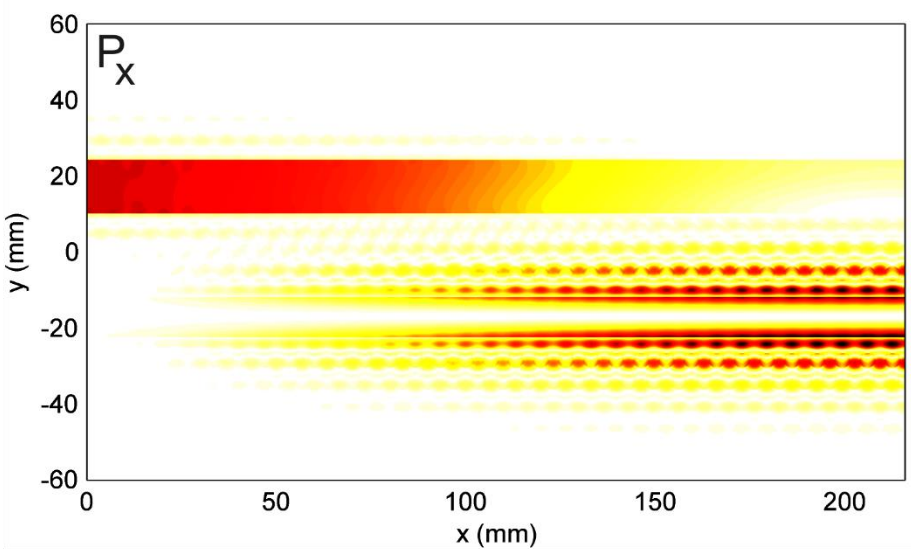
- Supermodes of the coupler:
  - Linear superposition of an accelerating and a transverse mode.
  - Field in the narrow waveguide resembles the accelerating mode.
  - Field in the large waveguide resembles a classic transverse mode.

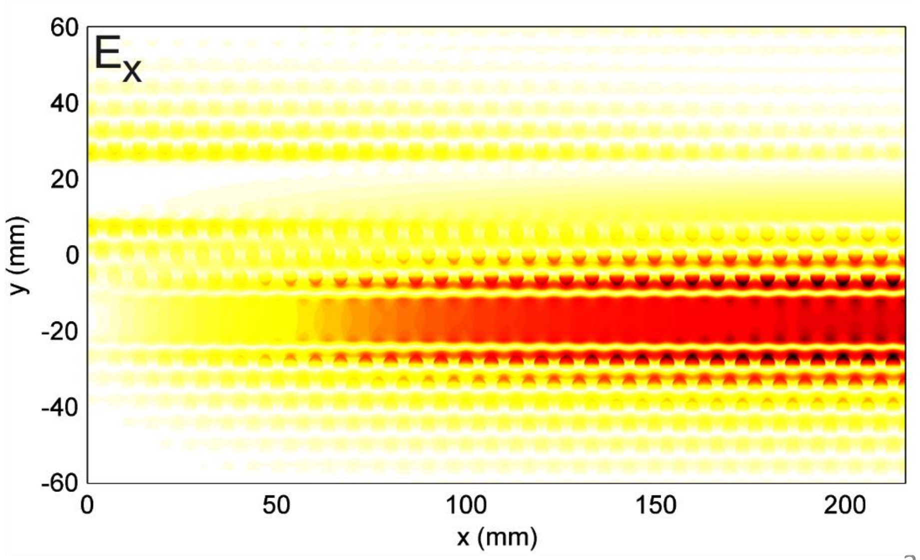




Design of PC input couplers

- Field evolution inside the PC coupler:
  - Longitudinal Poynting vector P_x vs. accelerating field E_x.
  - The input field can be efficiently injected into the narrow waveguide.
  - After a beat length power is concentrated into the accelerating mode.





Copropagating schemes for Dielectric Laser Accelerators

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

1) Slotted waveguide @ 5 μm

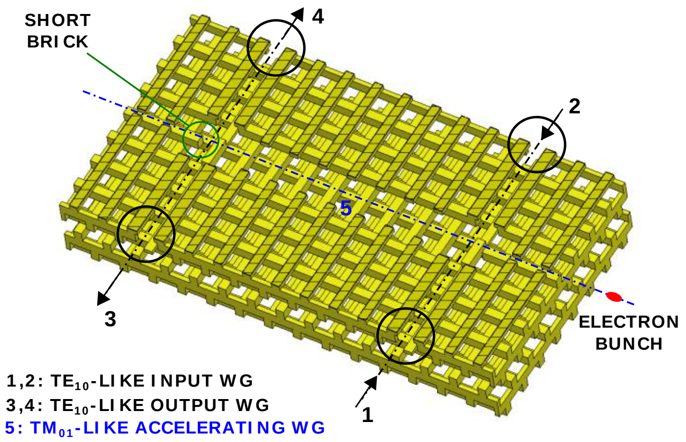
$[0.4 < \beta < 0.75,\ Zc = 1.5\ \mathrm{k\Omega}]$

2) 2D photonic crystal waveguide

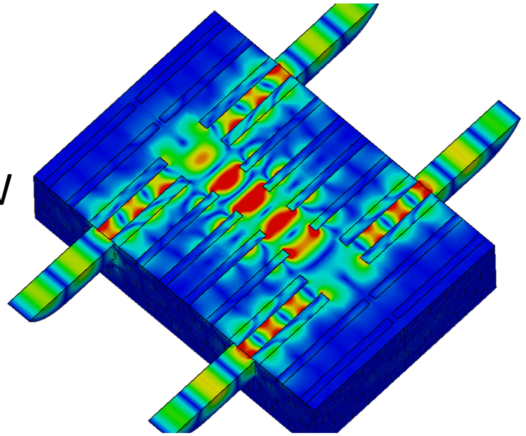
$[\beta = 1]$

3) Woodpile @ 5 μm

$[\beta = 1, Z_c = 11.4\ \mathrm{k\Omega}]$



~ 1 GV/m
@ P_inj=1 kW

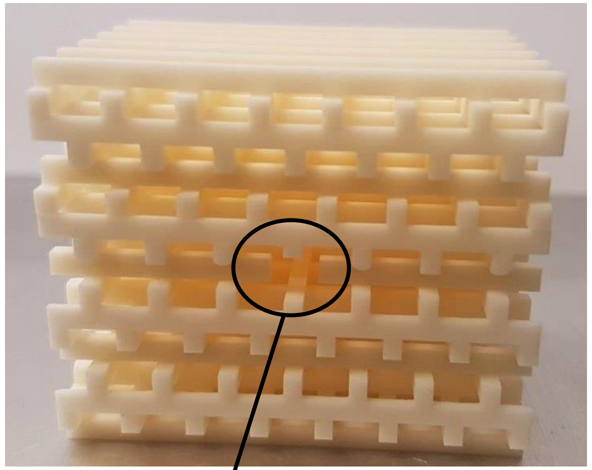


3) Woodpile

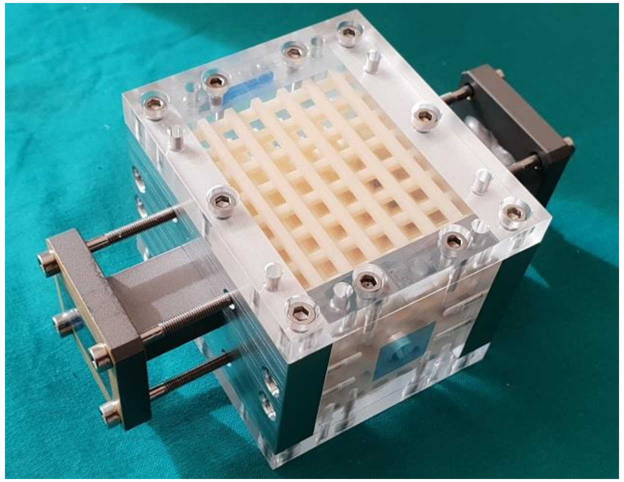
- Composed by a “pile” of rectangular $w \times h$ bricks disposed in layers stacked in the vertical direction, each layer rotated of 90° with respect from the layer below, whose centers are distant a period d.

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

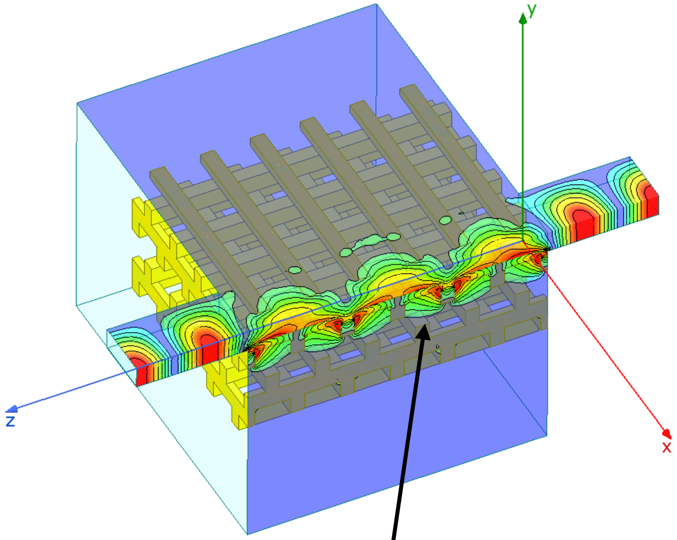
- The guided mode can be either a ‘launch’ transverse electric mode (TE10-like) or a mode suitable for particle acceleration (TM01-like).



‘Hollow-core’ defect channel



Woodpile waveguide



Electric field inside defect channel

G. S. 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.

3) Woodpile

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

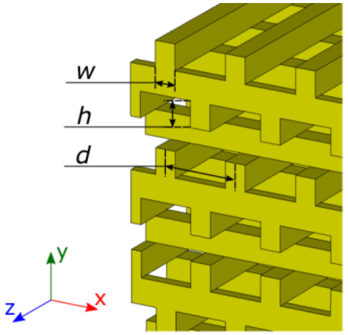
- The band-gap can be calculated using the MIT Photonic Bands (MPB) tool considering an unit cell with periodic boundary conditions.

- The design procedure has been carried out using **normalized frequency and normalized dimensions**, as usual for any EBG design.

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

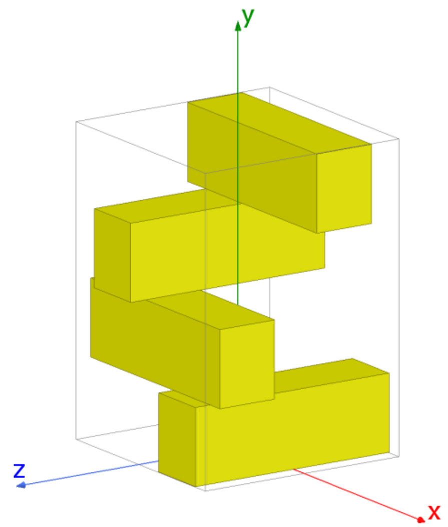
- By setting the period ***d*** the operating frequency can be selected : in order to operate at $\boldsymbol{f_c}$ **= 193.6 THz**, we choose $\boldsymbol{d}$ **= 645 nm**.

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

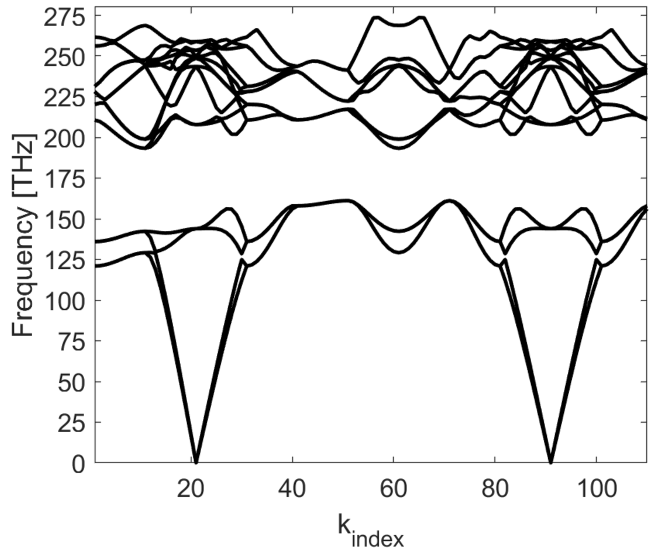


width (**w**) = 182 nm

height (**h**) = 228 nm



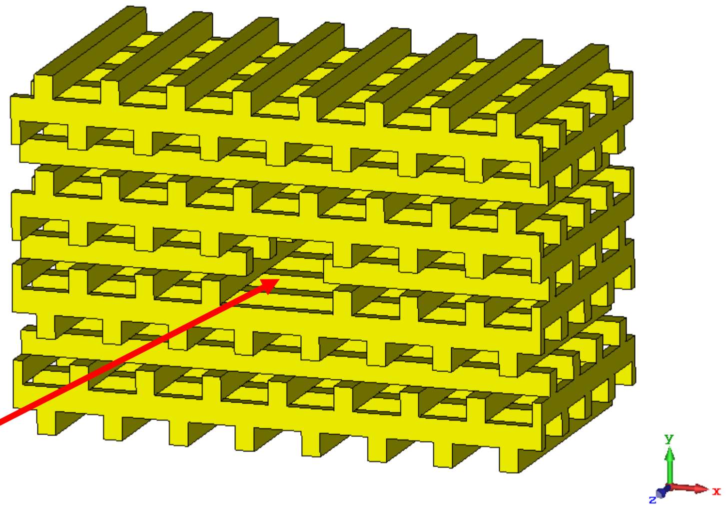
Woodpile unit cell

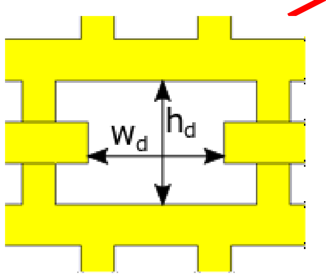


3) Woodpile

- 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.

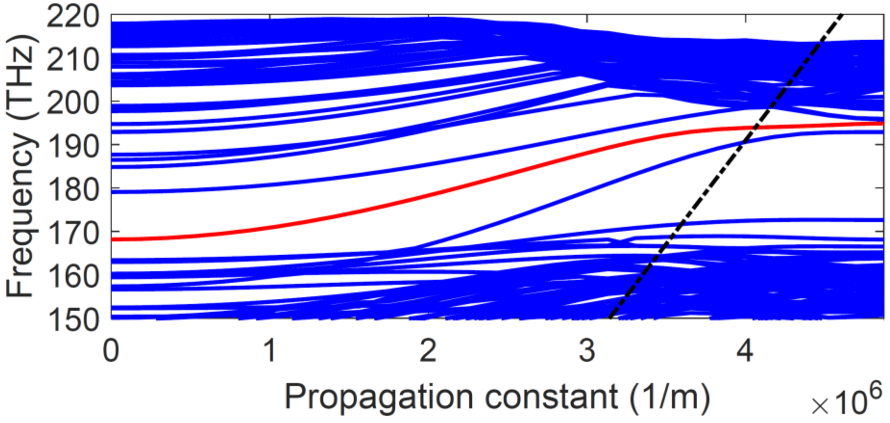




Hollow core defect dimensions:

$\mathbf{w_d}$ = 752 nm
$\mathbf{h_d}$ = 684 nm

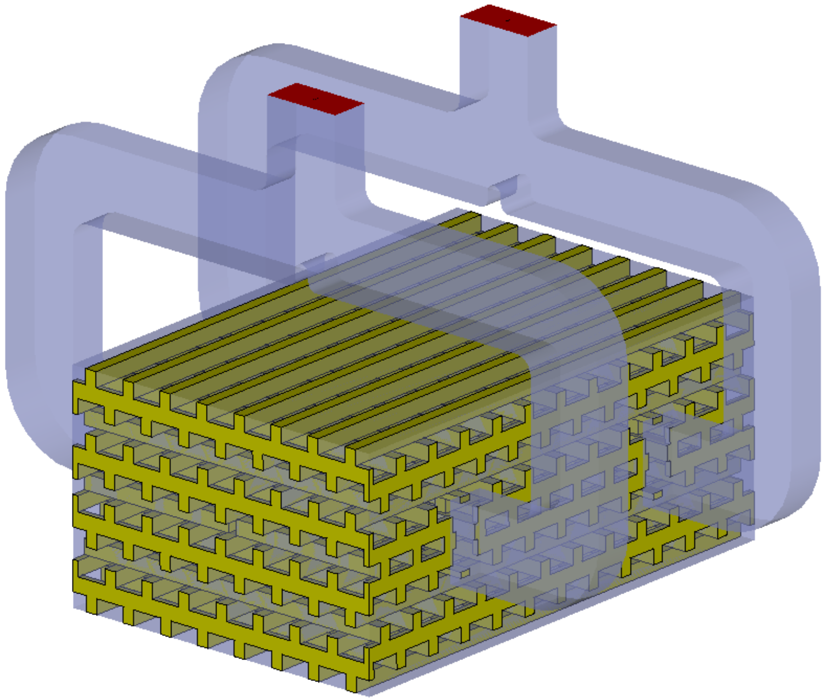
The **length** of the device along the defect direction (z axis) will depends on the desired output energy.



'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.

1550 nm hollow-core woodpile coupler (1/3)



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

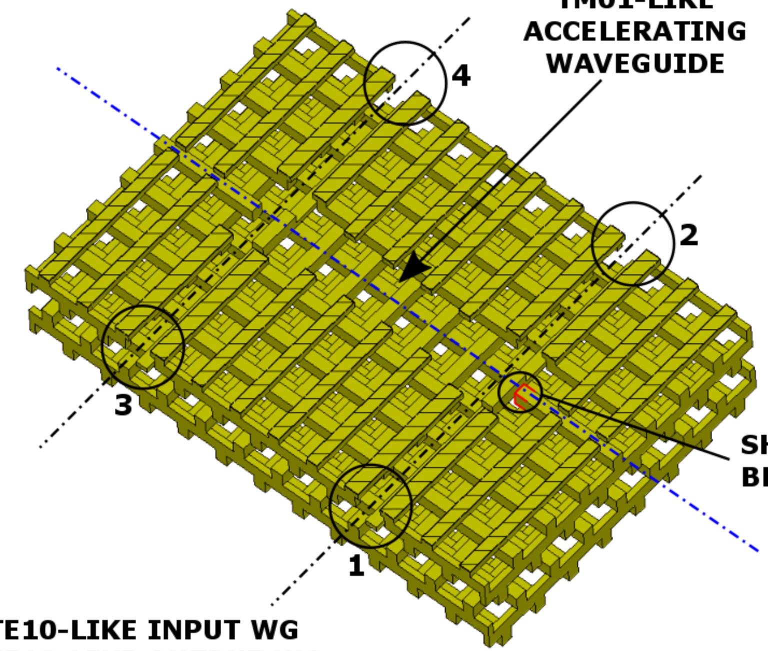
- Wave is injected (and extracted) into the woodpile coupler by using two waveguide **splitters** (or optical fibers at optical frequencies).

- 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.



1550 nm hollow-core woodpile coupler (2/3)

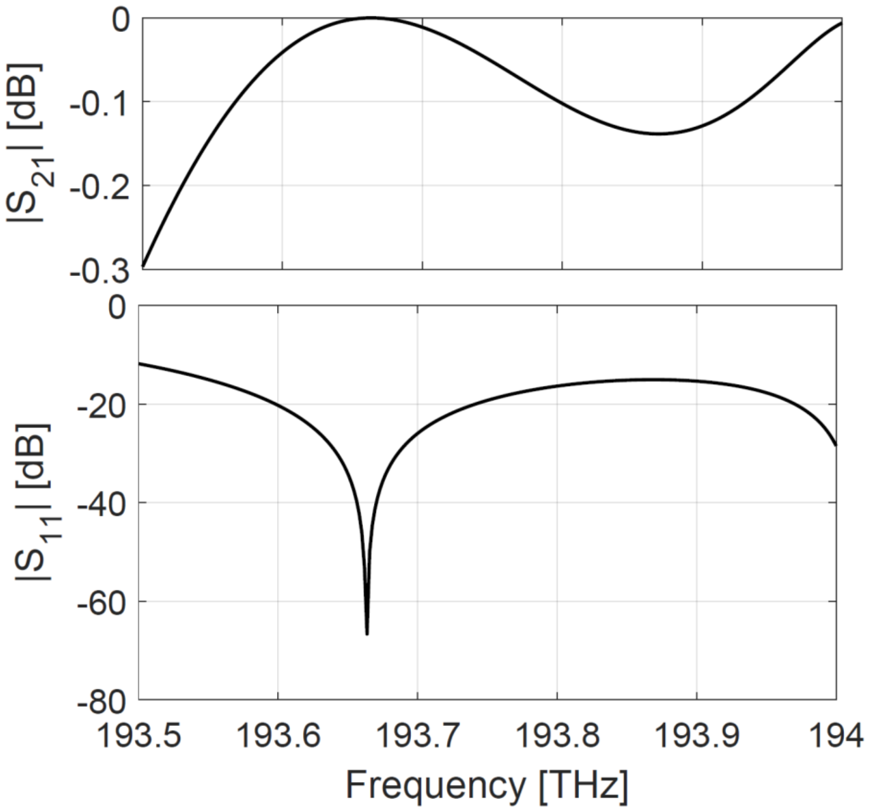
- Woodpile coupler tuned, in terms of S-parameters, to:

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 193.56-193.8 THz**.

- Full mode conversion at $\mathbf{f_0 \approx 193.66}$ **THz**.

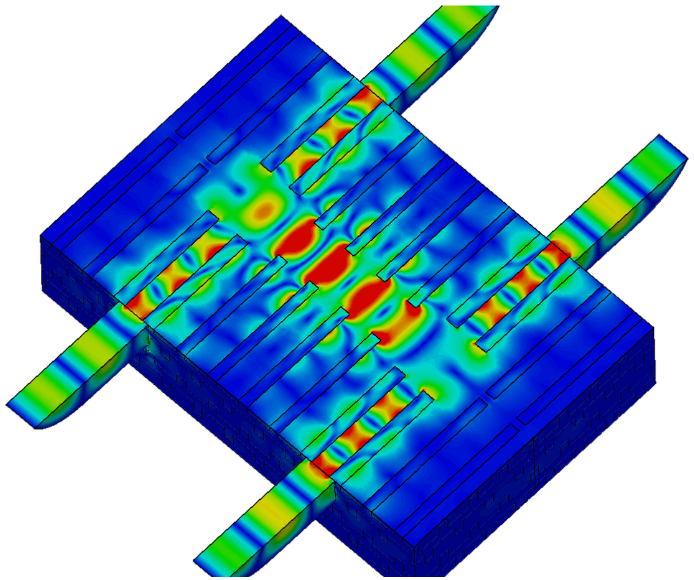


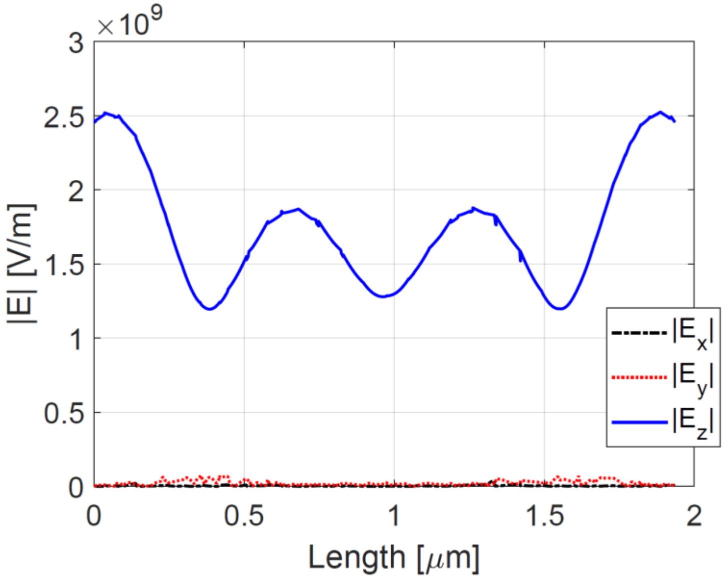
1550 nm hollow-core woodpile coupler (3/3)

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

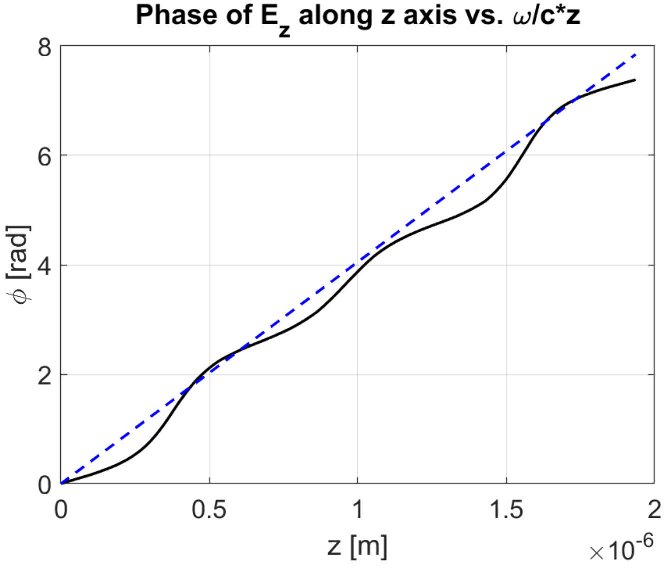
a) the longitudinal component |Ez| is predominant;

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





Acc. gradient of 2 GV/m along hollow-core channel with 500 W input power.



TM01-like mode synchronous with speed of light @ 193.66 THz.

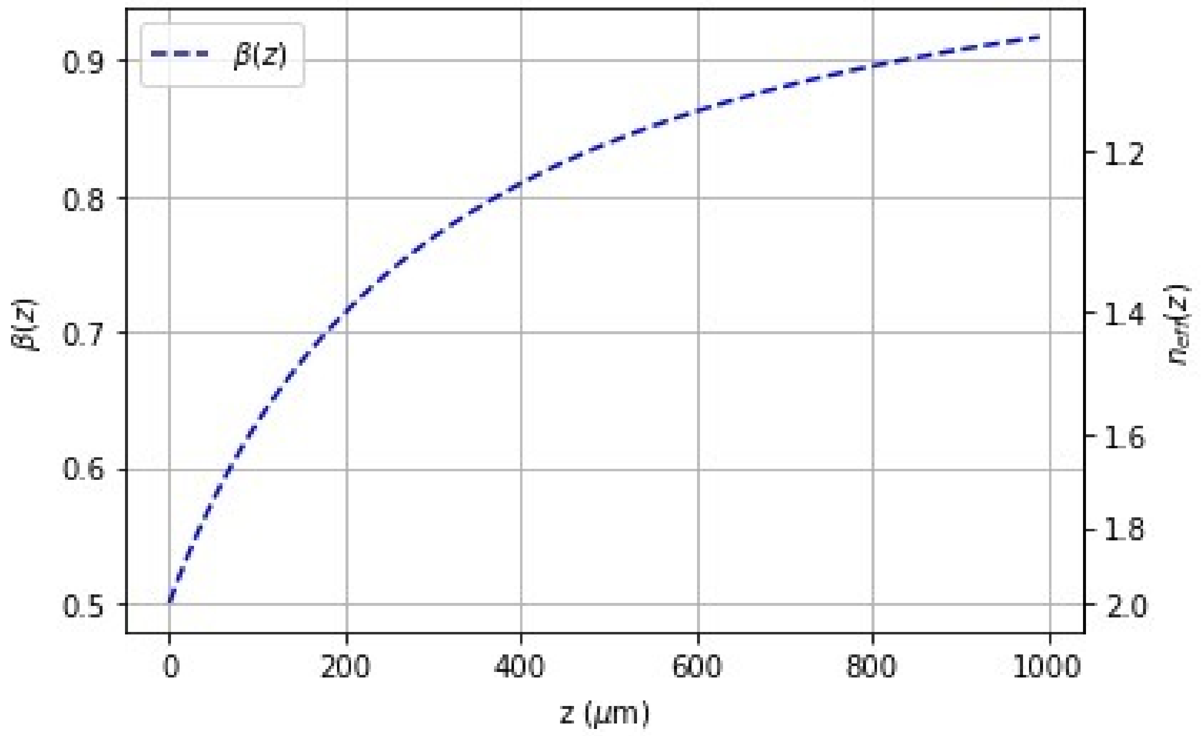
Single particle relativistic equation of motion **integration**

$$p^2 = \left(\frac{p^2}{c^2} + m^2\right) v$$

$$v = \frac{p}{\sqrt{\frac{p^2}{c^2} + m^2}}$$

$$\frac{dz}{dt} = \frac{p}{\sqrt{\frac{p^2}{c^2} + m^2}}$$

$$\frac{dp}{dt} = eE(z,t)$$



Where E=0.7 GV/m*

*1.4 GV/m damage threshold for silcon

Single particle relativistic equation of motion **integration**

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"safe" range
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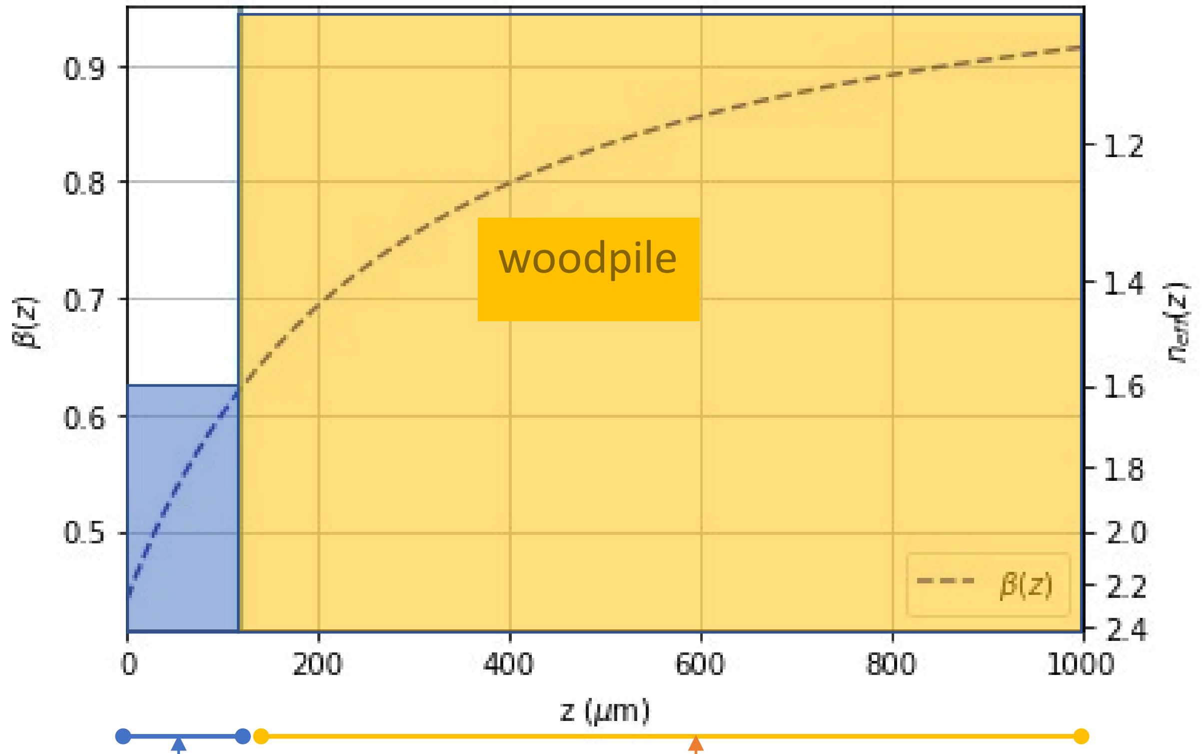


Tapered Slotted waveguide
$\mathbf{0.4 < \boldsymbol{\beta} < 0.63}$

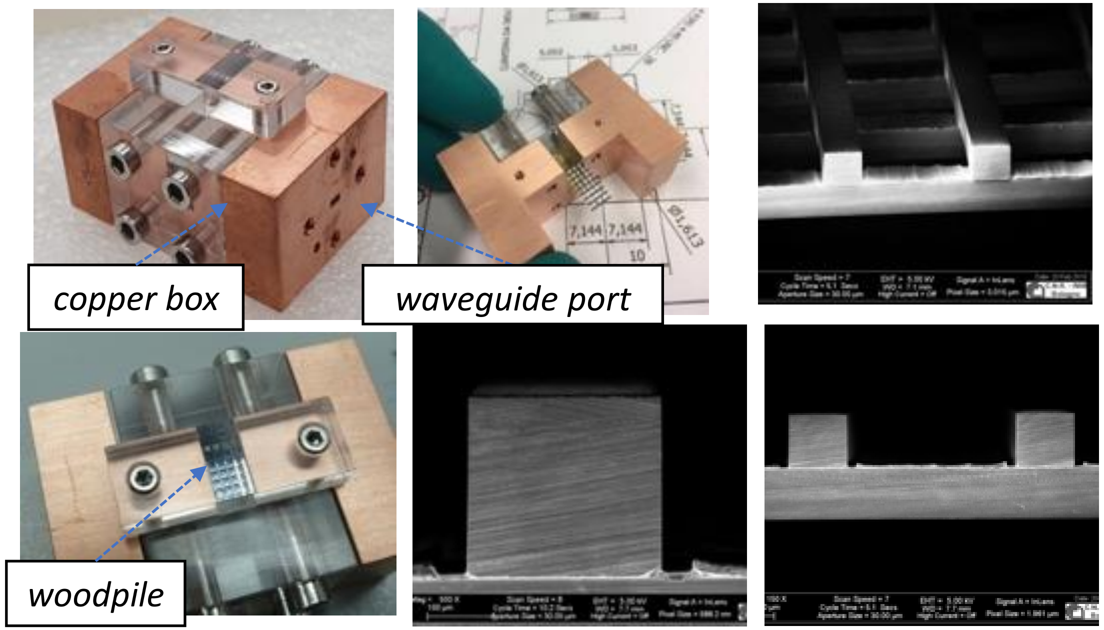
Tapered defect-Woodpile
$[\boldsymbol{\beta} = \mathbf{0.62 - 1}]$

Fabrication

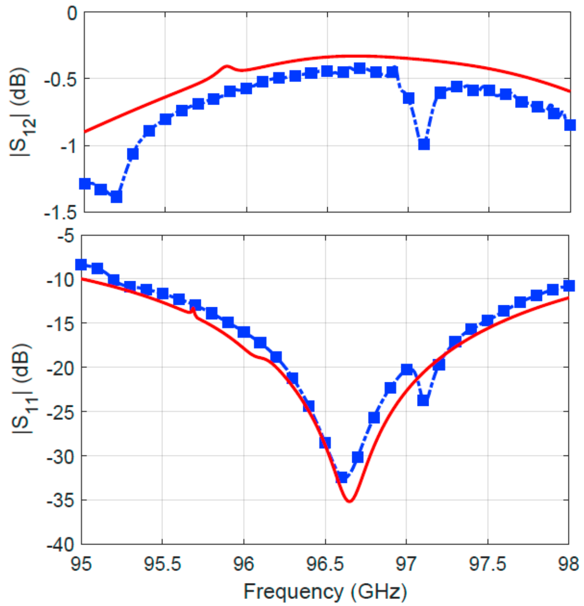
Silicon woodpile waveguide: fabrication & cold test at scaled at mm-wave frequencies

- high speed and **precision dicing saws**
- **silicon wafers** 850 µm thick with resistivity > 3 kΩcm
- **stacking together 9 silicon** layers
- **geometrical tolerance of 10 µm**

Design is frequency independent and valid at any working wavelength.

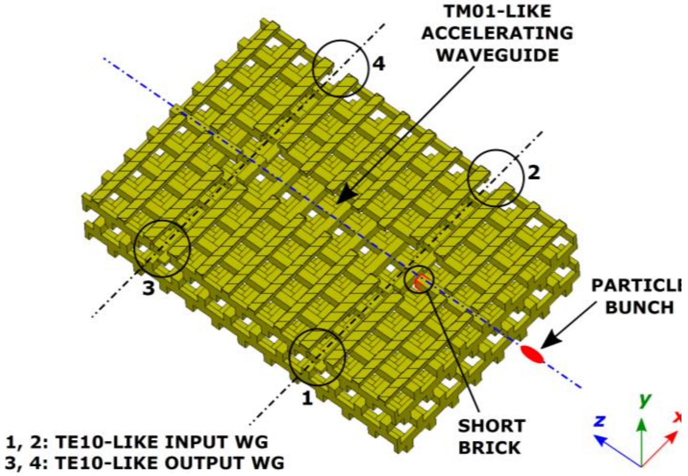


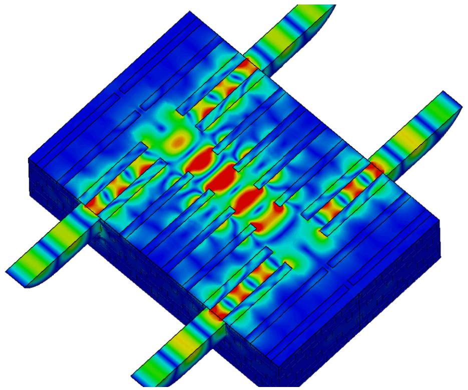
Manufactured dielectric PhC woodpile structure



Simulated vs Experimental S-parameters

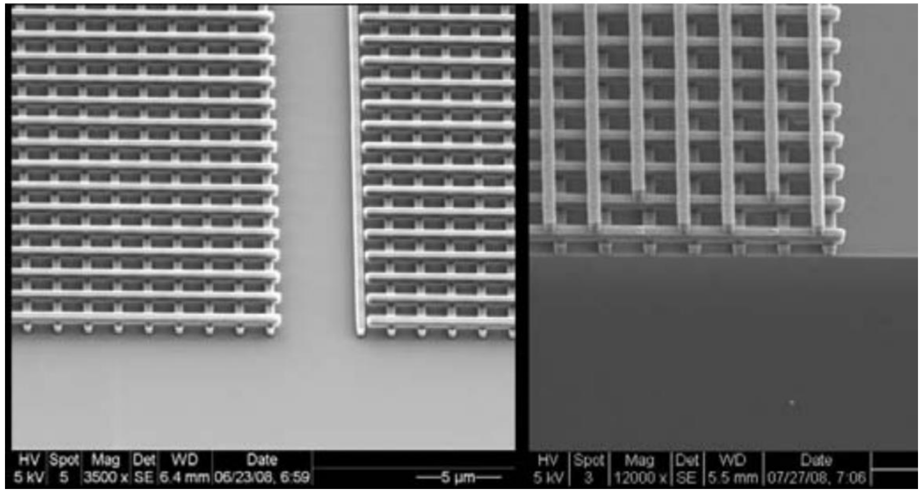
[G. Torrisi *et al.*, *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 4, pp. 347-350, 2020]



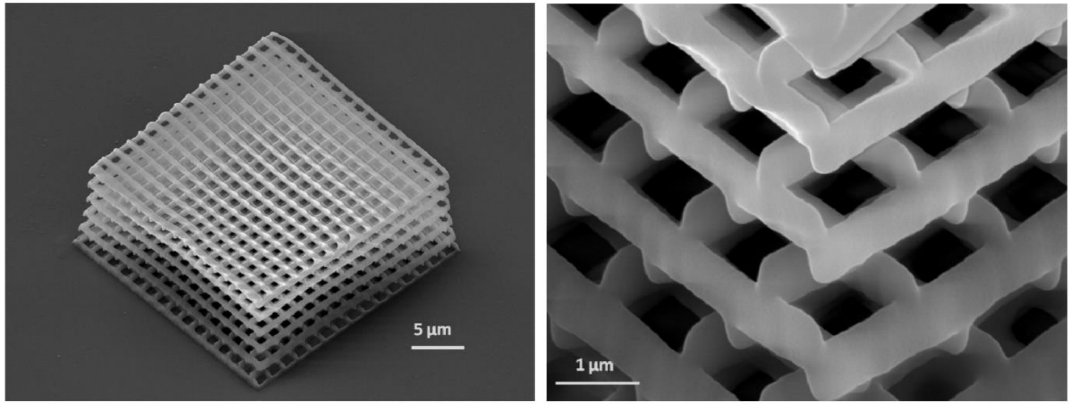


Woodpile structure fabrication - overview

- **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.

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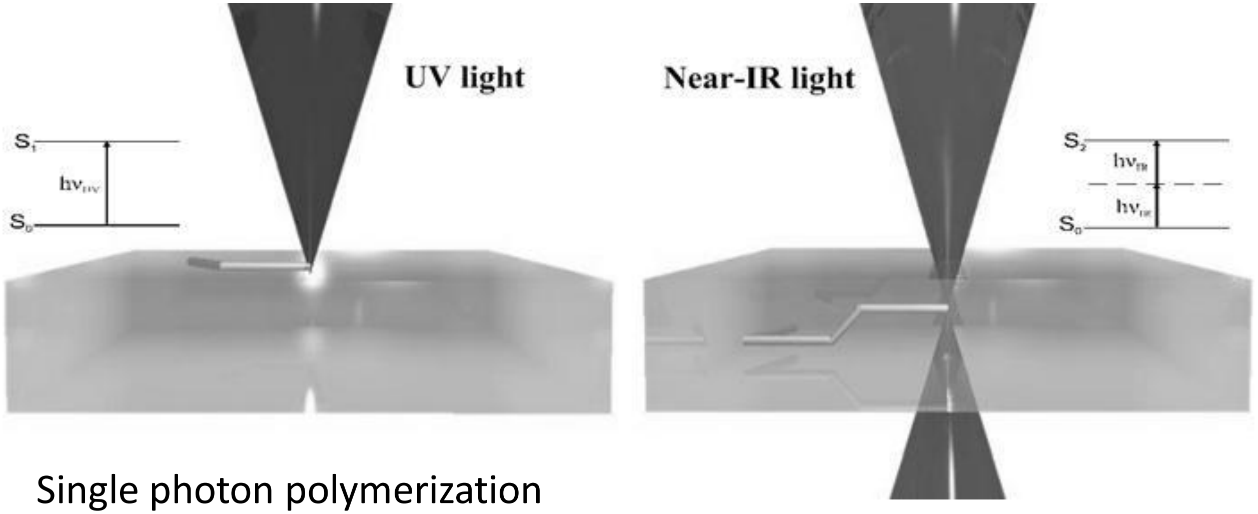
3D printing at the micro- / nano- scale

Two photon polymerization

Femtosecond pulsed laser to induce resist polymerization

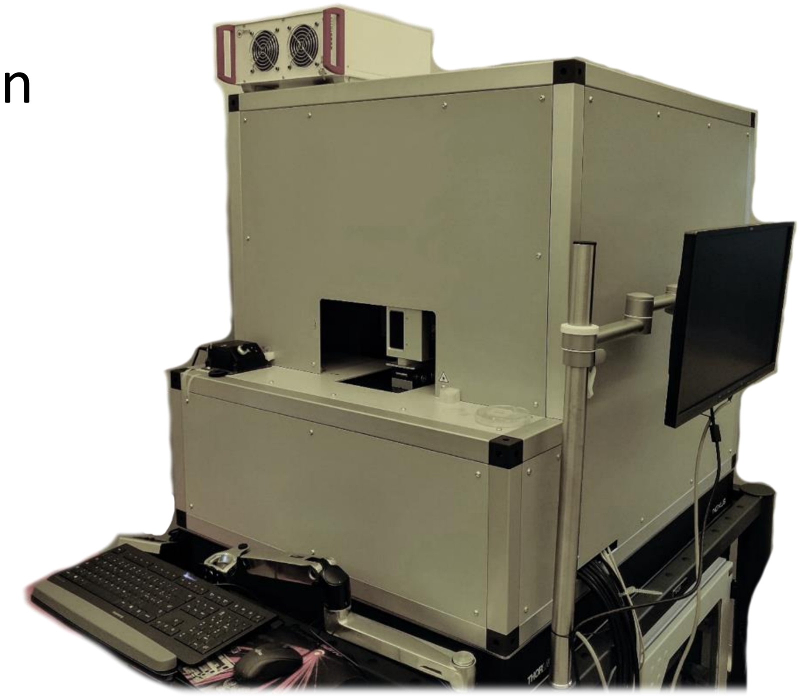
100x objective



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

Two photon polymerization: higher resolution, polymerization inside volume

Laser nanoFab



M4D System by Laser nanoFab
TPP setup

CVD / PECVD deposition of Si

AIM: obtain the designed Dielectric PC structure starting from the TPP printed structure

Fabrication of the Si woodpile micrometric structure by covering the polymeric structure obtained by TPP with Si deposited by CVD techniques as

- PECVD (a-Si:H)
- LPCVD (a-Si:H or polySi)

PECVD

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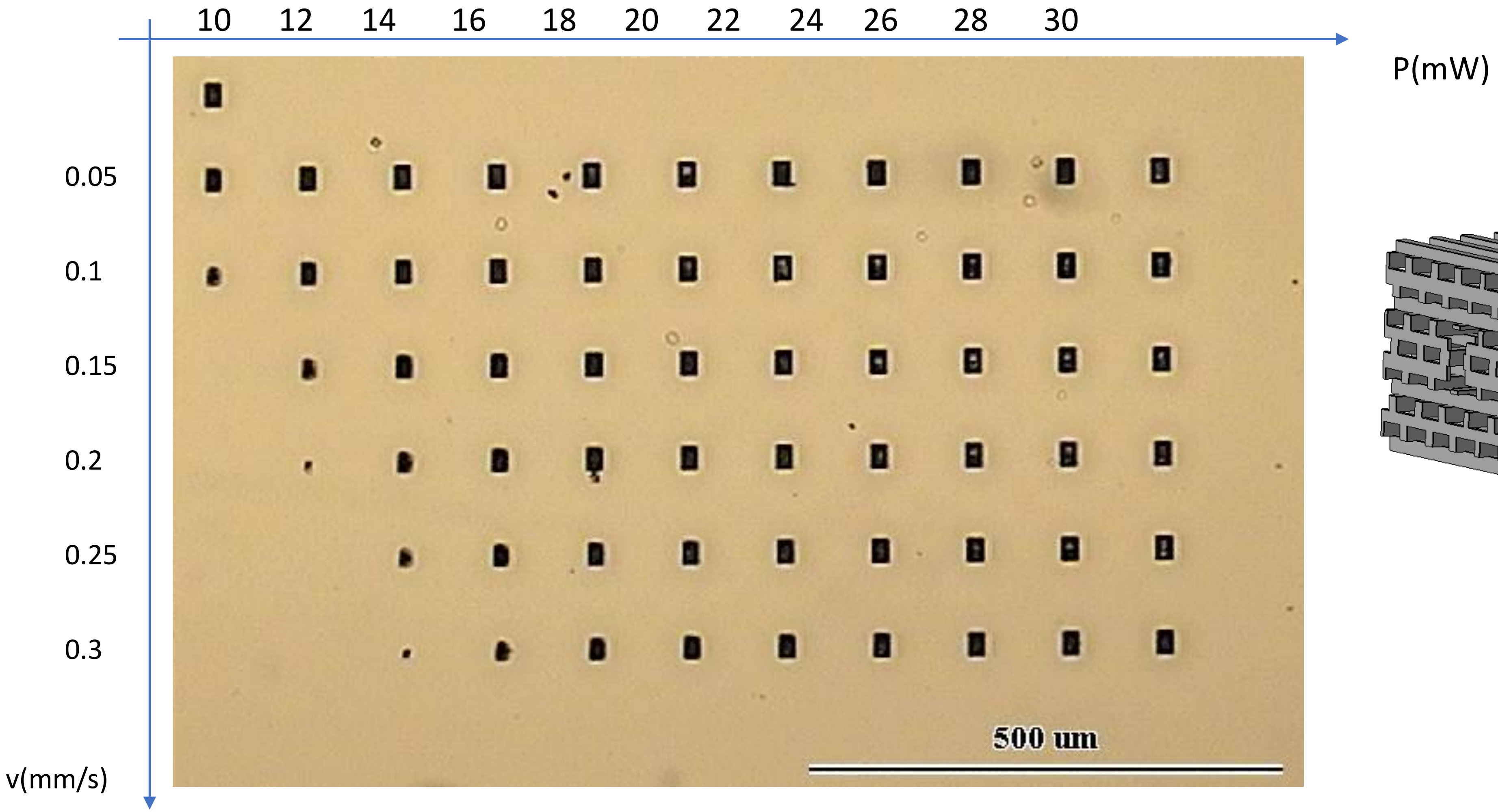
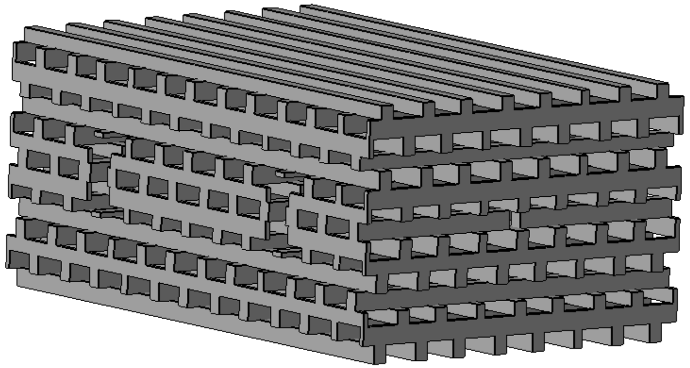
TPP test pattern: a matrix with many woodpile structures (5 μm)
ORMOCOMP / glass

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

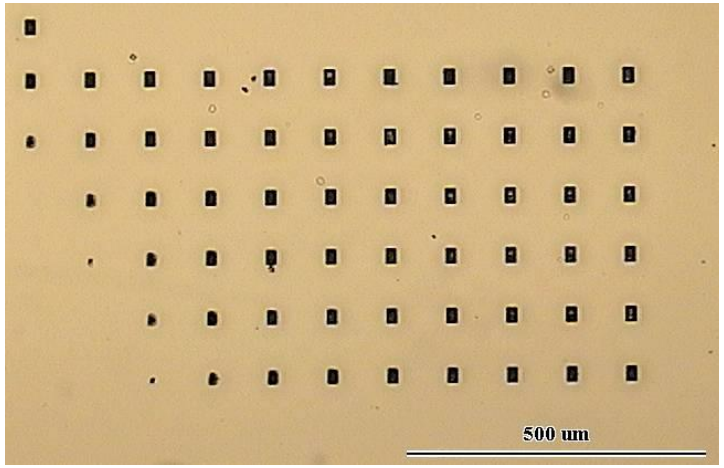




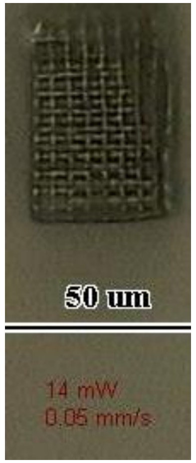
Test of adhesion and quality of the 3D printed structures

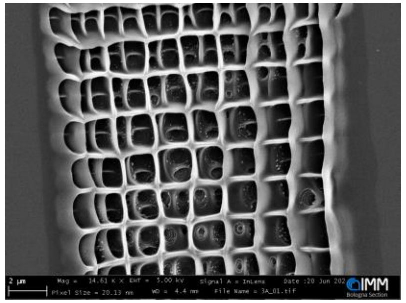
- Pyrolysis (graphitizaton) of the polymer @ 450°C and @ 690°C in Ar
- SEM observation to see **adhesion, quality of the 3D printing and to find the best printing parameters**

Good adhesion of the printed structure
to the substrate



- **Printing to be optimized**
- **<u>Results are promising,</u>**
- **Best parameters (14mW, 0,05 mm/s)**





On going:

- Deposition of a-Si-H by PECVD and thermal CVD on the graphitized woodpile structures to test the % of coverage of the printed structures on the whole volume of the woodpile
- TPP fabrication of new woodpile structures on fused silica with optimized TPP optical setup

Towards 2023
- Optimization of Si deposition
- Etching tests of the skeleton after Si deposition

Towrads 2024:
- SEM characterization of the morphology and geometrical quality of the woodpile structure

Submitted Proposals under evaluation:

Pathfinder Call

Micro Optical Dielectric AcceLerator (MODAL)

[~3 M€]

European Commission | Funding & tender opportunities

Single Electronic Data Interchange Area (SEDIA)

PROGRAMME	CALL	FUNDING SCHEME	PROPOSAL ID	ACRONYM
HORIZON	HORIZON-EIC-2022-PATHFINDEROPEN-01	HORIZON-EIC	101098598	MODAL

- Study of the beam transport and focusing to injection into the interaction structure from the **CANDLE** electron gun
- input beam can be obtained starting from the RF gun based 5 MeV electron linear accelerator **AREAL (Advanced Research Electron Accelerator Laboratory)** by using standard magnets for focusing and emittance reduction
- to control the electron beam parameters, the experimental set-up will use 5 MeV AREAL RF gun, focusing solenoid, ad-hoc fabricated quadrupole triplet, vertical and horizontal corrector magnets placed before the vacuum chamber.

Proposals ongoing:

INFN 5th Nat. Committee, supporting technological R&D for accelerators and detectors: MIniaturised aCceleRatOrs Network (**MICRON**) [around 50 k€ on dielectric struct*]

MICRON (**MI**niaturised a**C**cele**R**at**O**rs **N**etwork)

*150 k€ all

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MICRON (**MI**niaturised a**C**cele**R**at**O**rs **N**etwork)

INFN LNS

µICRON MIniaturised aCceleRatOrs Network

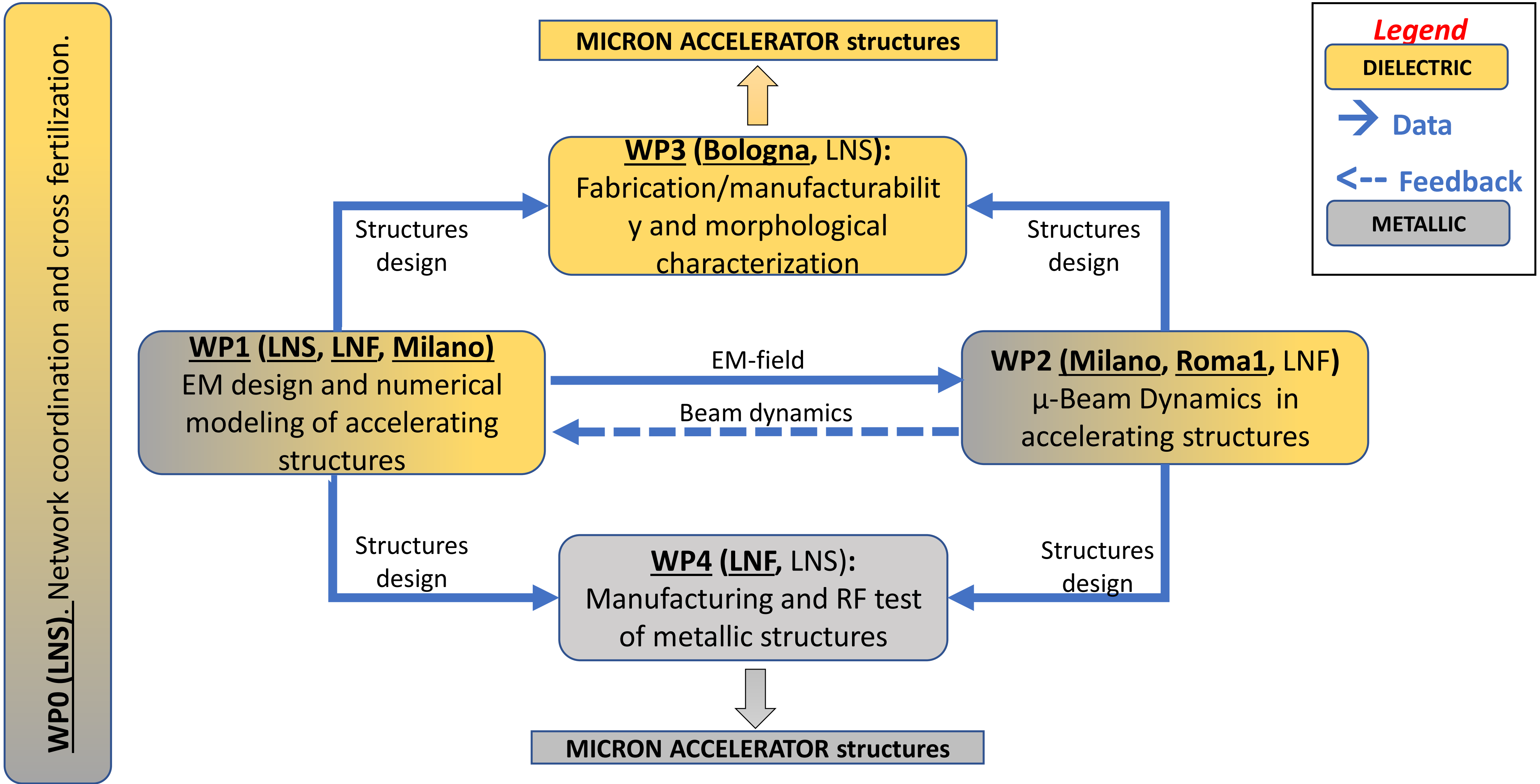
*150 k€ all

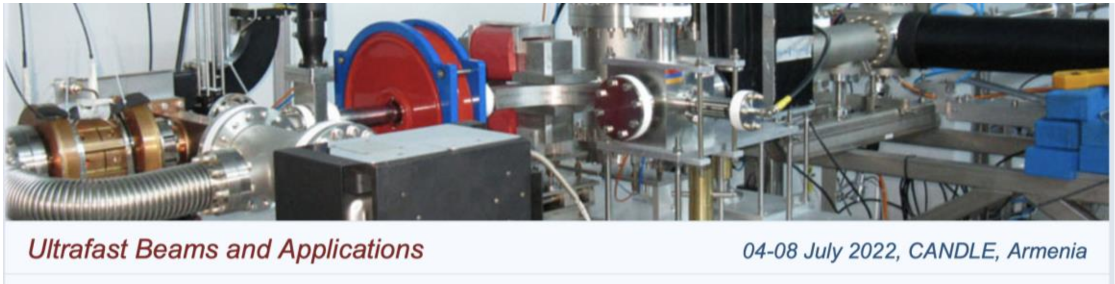
Proposals ongoing:

INFN 5th Nat. Committee, supporting technological R&D for accelerators and detectors: MIniaturised aCceleRatOrs Network (**MICRON**) [around 50 k€ on dielectric struct*]

MICRON (MIniaturised aCceleRatOrs Network)

μICRON
MIniaturised aCceleRatOrs Network

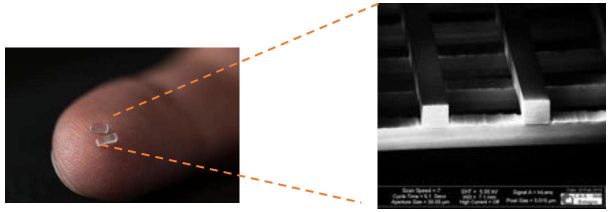




THANK YOU!

Copropagating schemes for Dielectric Laser Accelerators

G. Torrisi[1], G. S. Mauro[1], A. Bacci[2], D. Mascali[1], A. F. Usmani[1]
A. Locatelli[2,3], C. De Angelis[2,3]
G. Della Valle[4],
R. Rizzoli[5], V. Bertana[6], S. Marasso[6]
and G. Sorbello[7,1]



[1]Istituto Nazionale di Fisica Nucleare–Laboratori Nazionali del Sud (INFN-LNS), Via S. Sofia 62, 95123 Catania, Italy
[2]Istituto Nazionale di Fisica Nucleare–Sezione di Milano, Via Celoria 16, 20133 Milan, Italy
[3]Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia, Via Branze 38, 25123 Brescia, Italy
[4]Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, I-20133 Milano, Italy
[5]Consiglio Nazionale delle Ricerche Istituto per la Microelettronica e Microsistemi Unità di Bologna, Via Gobetti 101, Bologna,Italy,40129
[6]DISAT - Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy
[7]Dipartimento di Ingegneria Elettrica, Elettronica e Informatica, Università degli Studi di Catania, Viale Andrea Doria 6, 95125 Catania, Italy

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

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