Numerical Simulation and Beam Dynamics Study of a Hollow-Core Woodpile Coupler for Dielectric Laser Accelerators

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Dielectric Laser Accelerators: introduction

- **MOTIVATION**: strong need of particle accelerators working at higher and higher frequencies (reaching optical frequencies) to obtain high energy particle beams for research and medical applications.

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

- SOLUTION: employ dielectric structures in order to reach higher frequencies.

- Main advantages of DLA:

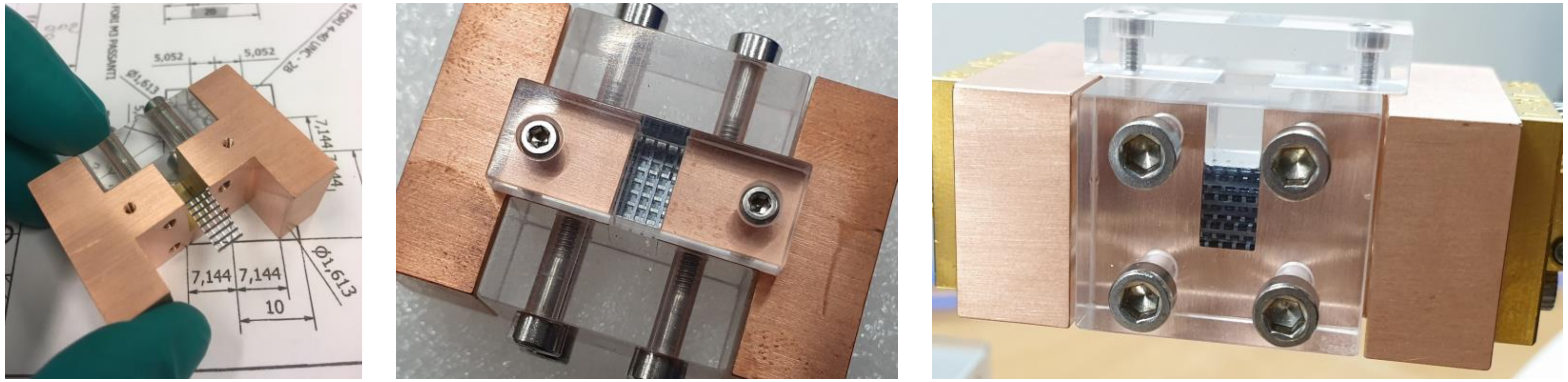
a) **larger damage threshold of dielectrics with respect to metals;**

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

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

- Compact dielectric accelerating devices are possible by employing the so called Electromagnetic Band Gap (EBG) structures based on the photonic crystals.

Employed frequency spectrum:
W-band (mm-waves)
for ‘practical’ reasons

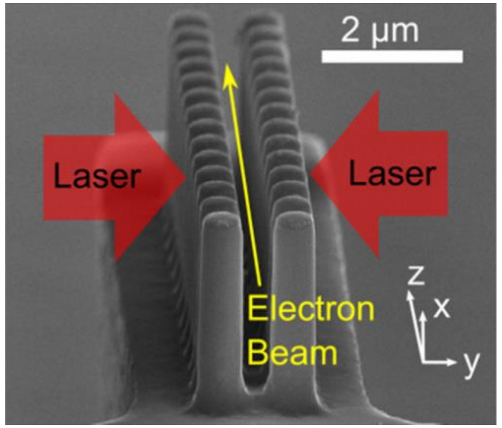


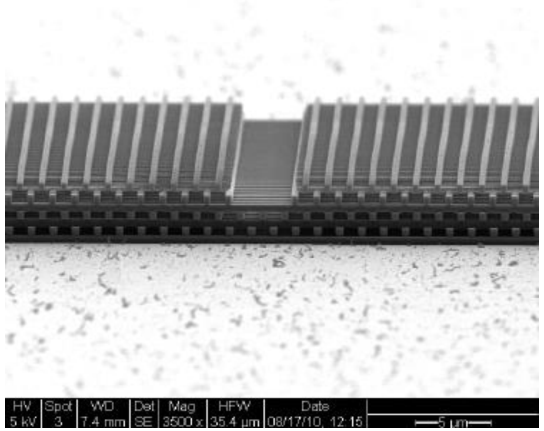
G. Torrisi *et al.*, "Design and Characterization of a Silicon W-Band Woodpile Photonic Crystal Waveguide," in *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 4, pp. 347-350, April 2020, doi: 10.1109/LMWC.2020.2972743.

Final application:

Wavelength: ~ 1 – 5 µm

All-optical
Dielectric Laser Accelerators (DLAs)





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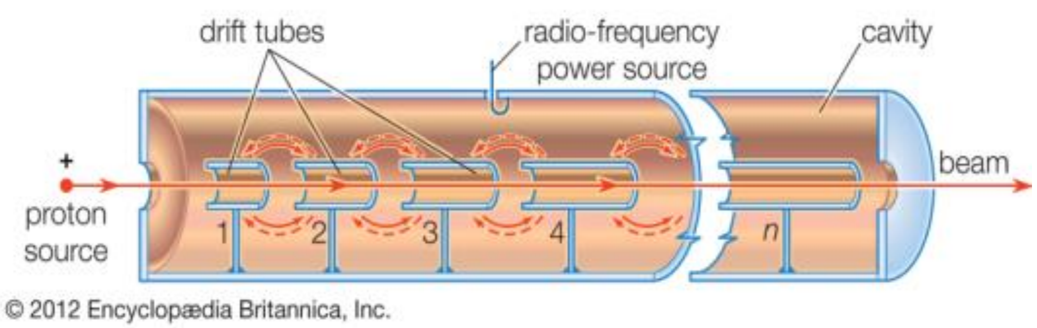
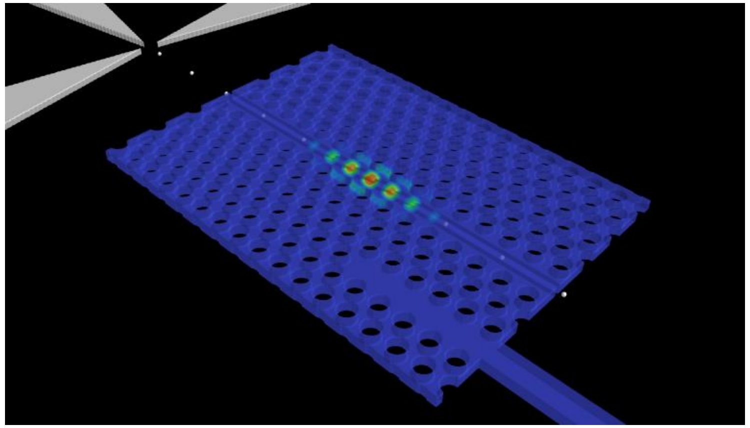
Dielectric Laser Accelerators: perspectives

1 M€ CONVENTIONAL ACCELERATOR



Length: tens of meters only for the DTL section.

100 k€ OPTICAL INTEGRATED DIELECTRIC LASER ACCELERATOR (DLA)



high-Q photonic-crystal cavity. (Courtesy of C2N)

Long term perspectives:

- **cost-effective** and **portable dielectric** particle accelerator for particle therapy;
- based on low-cost, **mass production micro-optical chips** driven by **solid state laser;**
- **accelerating gradients up to GV/m** vs. few MV/m of a metallic LINAc.

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.**

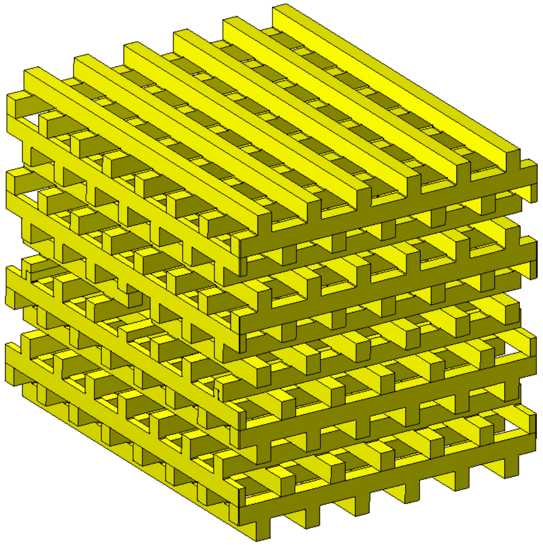
- **Introducing a defect into the lattice**, by removing or altering one element of the structure, **a guided mode can be trapped inside the structure.**

- For DLA use, defect is typically a linear hollow channel:

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

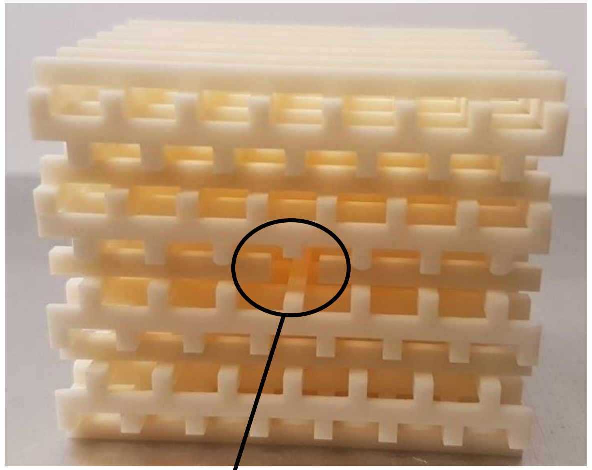
b) phase velocity equal to the particle velocity.

- For our pourposes, the chosen EBG structure is called woodpile.

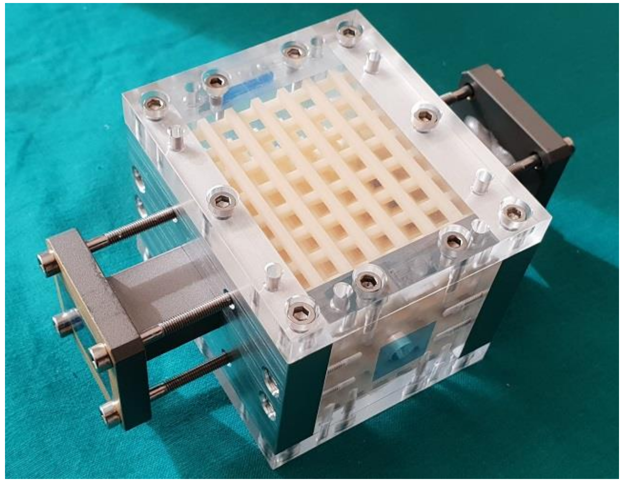


The woodpile structure (1/3)

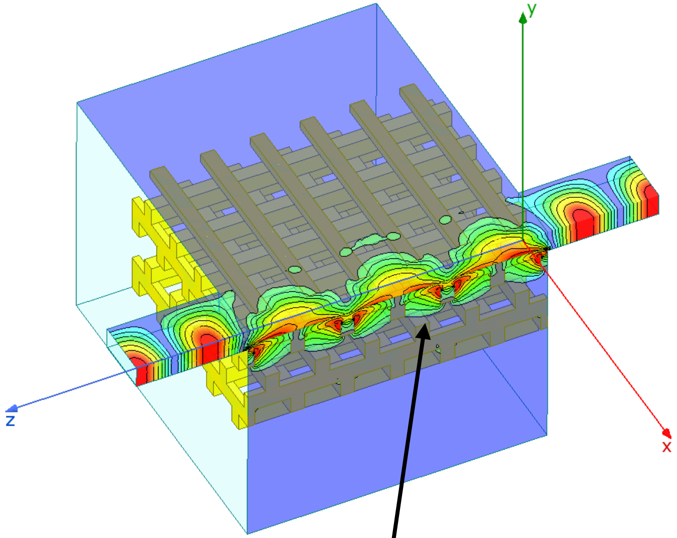
- Composed by a "pile" of rectangular bricks disposed in layers stacked in the vertical direction, each layer rotated of 90° with respect from the layer below, whose centres are distant a period *d*.
- Creating a so called "defect channel", one or more modes can be trapped inside the defect and thus 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



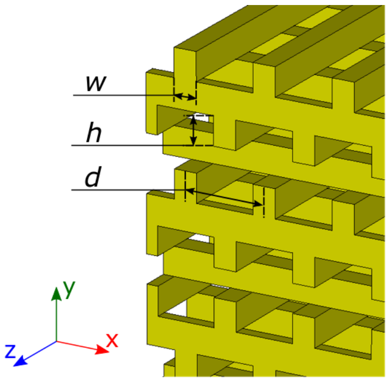
Electric field inside defect channel

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.

The woodpile structure (2/3)

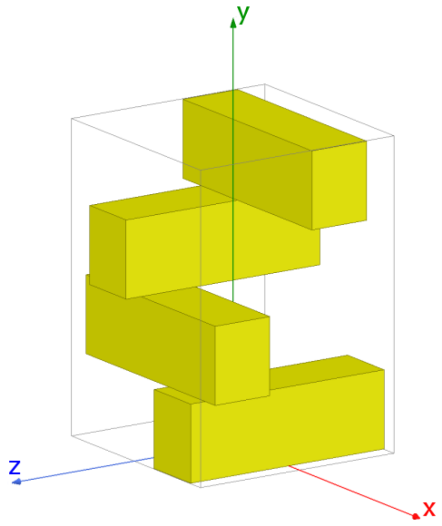
- The **unit cell** repeats in the stacking direction each four layers, creating a **frequency band-gap** where the EM propagation is suppressed.
- The band-gap can be calculated using the MIT Photonic Bands (MPB) tool considering an unit cell with periodic boundary conditions.
- Once the fundamental (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 = **90.505 GHz**, we choose ***d* = 1.38 mm**.

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

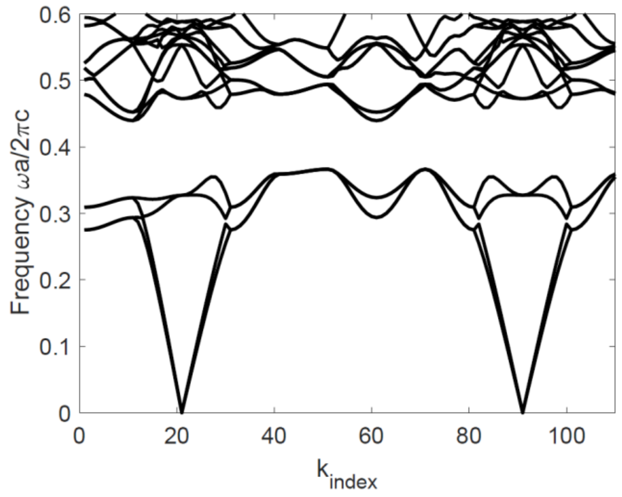


width (**w**) = 0.39 mm

height (**h**) = 0.49 mm



Woodpile unit cell

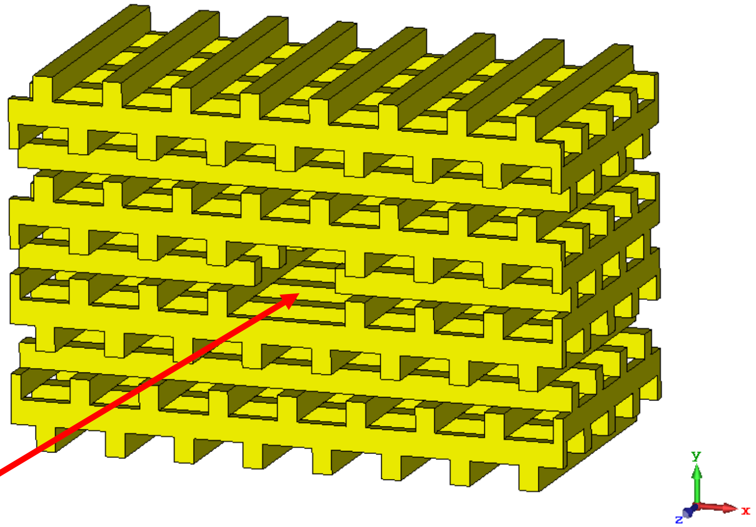


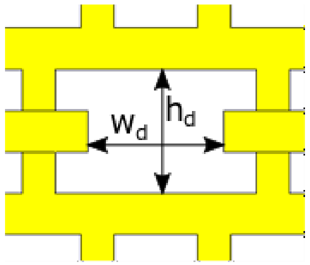
The design is frequency independent and valid at any working wavelength, provided that a **low loss material** with an appropriate dielectric contrast is available at the target operating frequency (in our case silicon with $\boldsymbol{\varepsilon}_r$ = 11).

The woodpile structure (3/3)

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

- The defect can be tuned to support a guided electromagnetic mode.

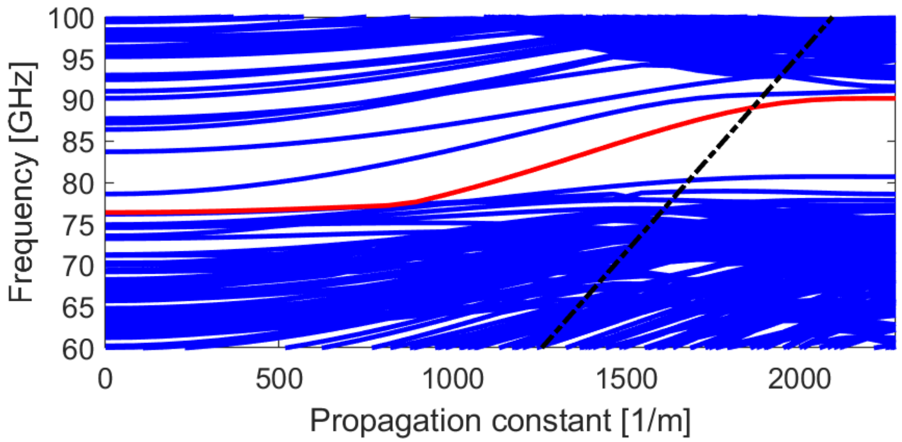




Hollow core defect dimensions:

$\mathbf{w_d}$ = 1.61 mm
$\mathbf{h_d}$ = 1.46 mm

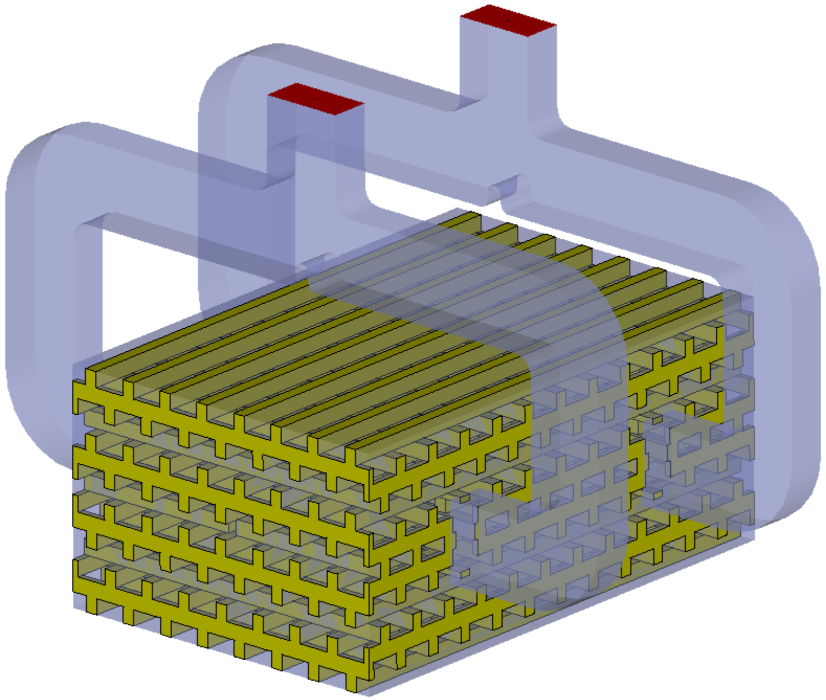
The **length** of the device along the defect direction (z axis) will depends on the desired output energy.



'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.

3.3 mm hollow-core woodpile coupler (1/3)



Structure dimensions: **11.04 mm x 7.32 mm x 16.56 mm**

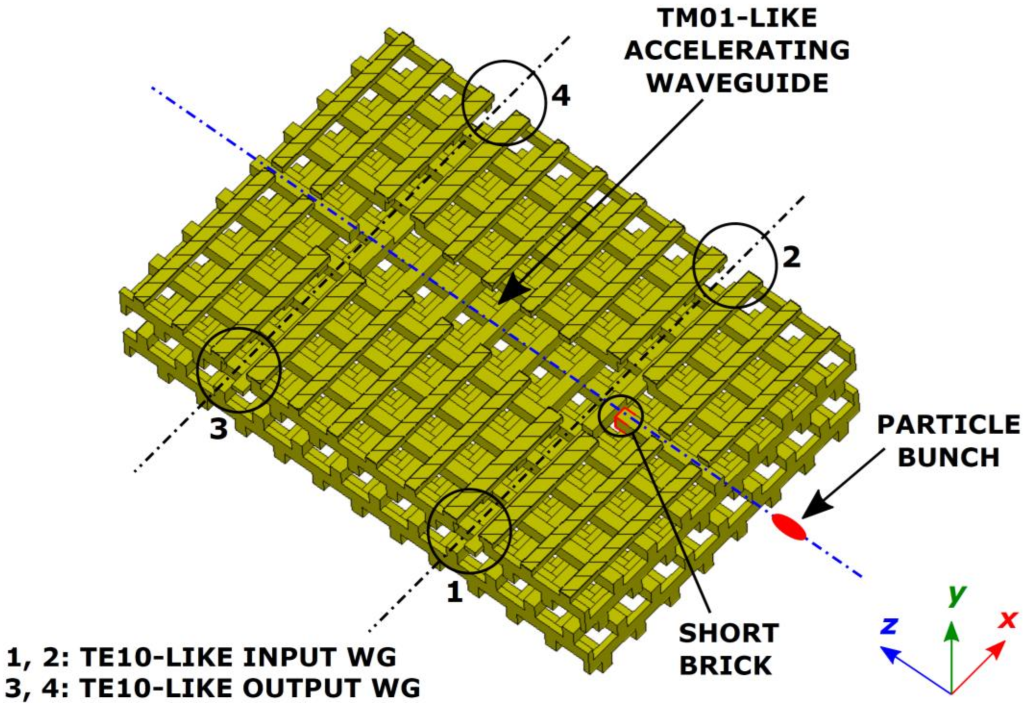
- Wave is injected (and extracted) into the woodpile coupler by using two waveguide **splitters** (or optical fibers at optical frequencies).

- 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.



3.3 mm hollow-core woodpile coupler (2/3)

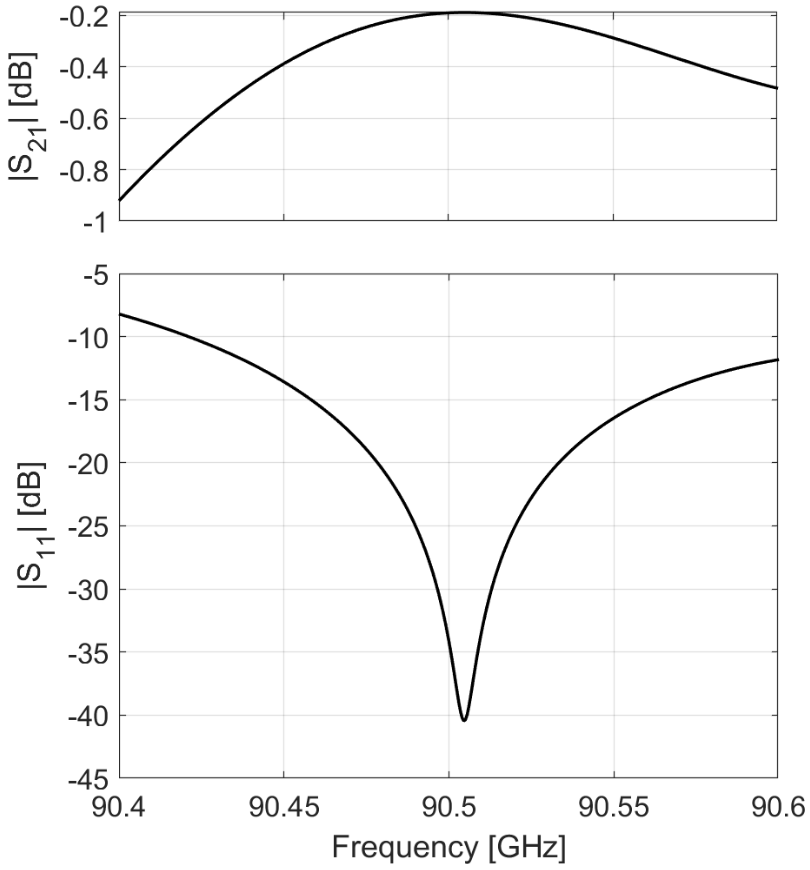
- Woodpile coupler tuned, in terms of S-parameters, to:

a) maximize the I/O wave transmission;

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

- The device possesses low loss (< 0.3 dB) inside the **operational bandwidth of 90.46 - 90.55 GHz**.

- Full mode conversion at $\mathbf{f_0 \approx 90.5}$ **GHz**.

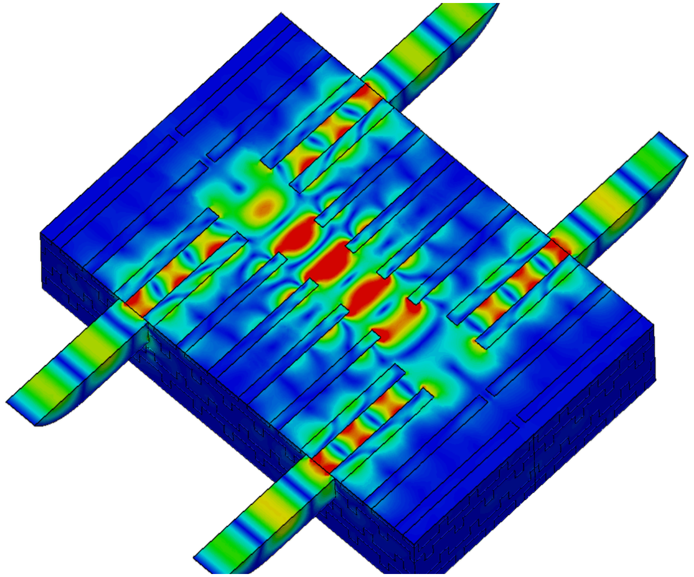


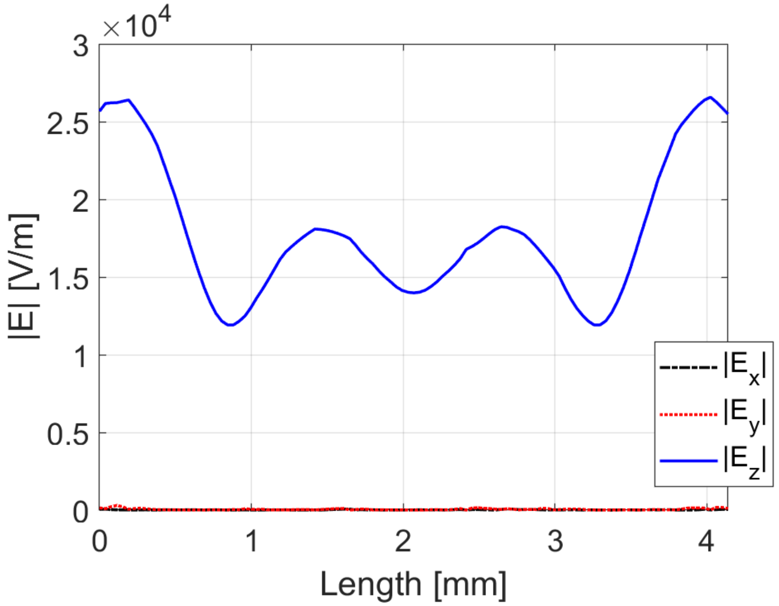
3.3 mm hollow-core woodpile coupler (3/3)

- From the electric field plot along the accelerating waveguide (**length** 3d = **4.14 mm**), it can be seen that:

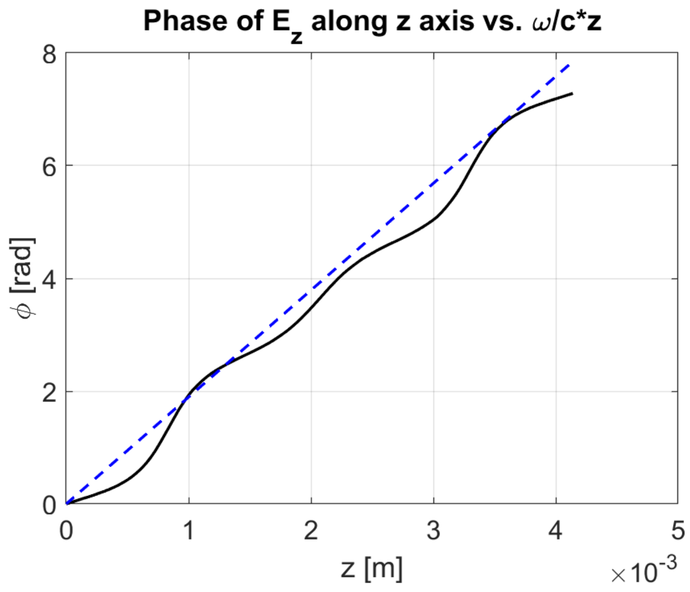
a) the longitudinal component |Ez| is predominant;

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





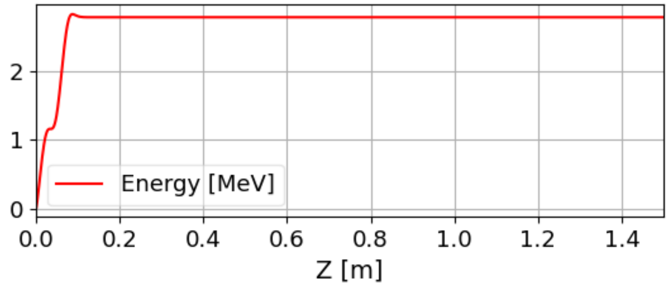
Note: input power has been set to 1 W



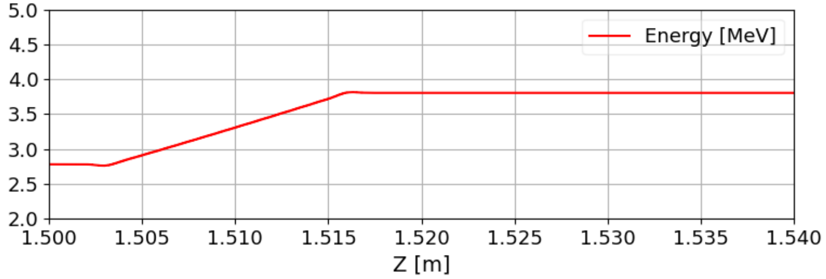
TM01-like mode synchronous with speed of light @ 90.5 GHz

Beam-dynamics calculations

- Preliminary BD calculations have been made by using the tracking code ASTRA.
- A photoinjector with $|E_{peak}|$= 60 MV/m has been used to obtain electron bunches at 2.8 MeV energy.
- The bunches have been injected into 12 mm long woodpile structure considering a semi-analytical TM_{01} acceleration field with a 200 MV/m |Ez| peak amplitude.

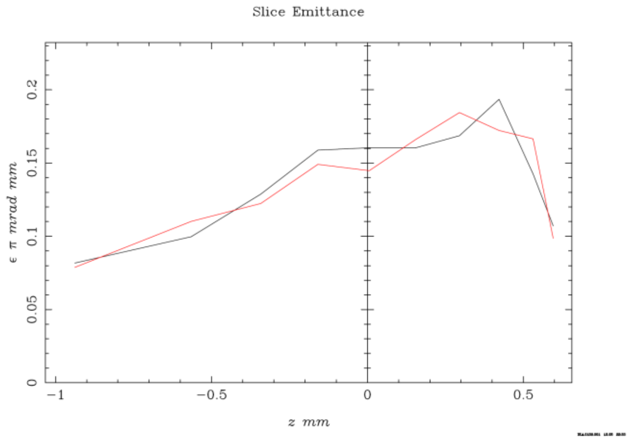


Photoinjector (1.5 m distant from the acc. woodpile waveguide)



Acc. woodpile waveguide (from 1.504 m to 1.516 m)

In about 12 mm the bunch gains ≈ 900 KeV.



Slice normalized projected emittance along the accelerating wave crest never exceeds 180 nm

Conclusions and perspectives

- The design of a compact dielectric coupler for future DLAs setups, has been presented.

- The hollow-core structure allows to convert an input TE_{10}-like mode, coming from two input waveguides, into a TM_{01}-like mode allowing on-axis electron acceleration.

➢ **Efficient and easy to tune structure, based on equivalent metallic couplers for electron accelerators.**

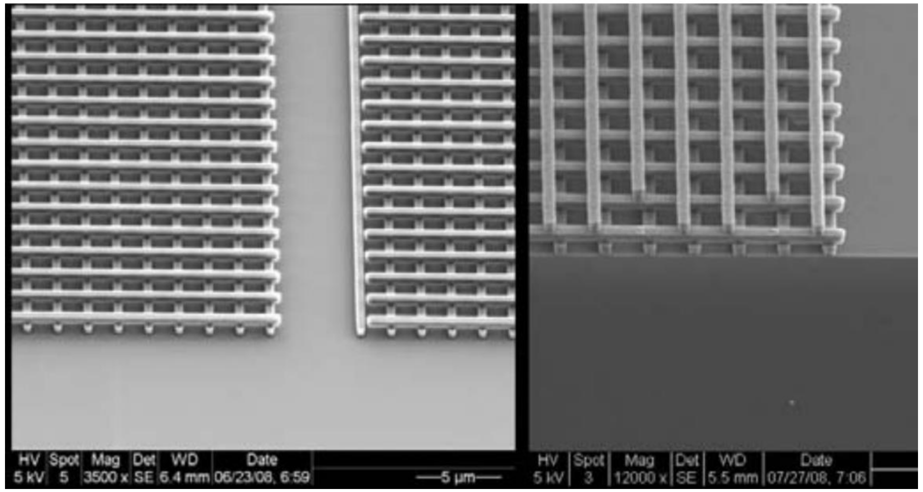
- Very good S-parameter performances obtained, together with an efficient mode conversion at f_0 = 90.5 GHz.

- The structure could represent a crucial component for the future tabletop DLAs operating at optical wavelengths.

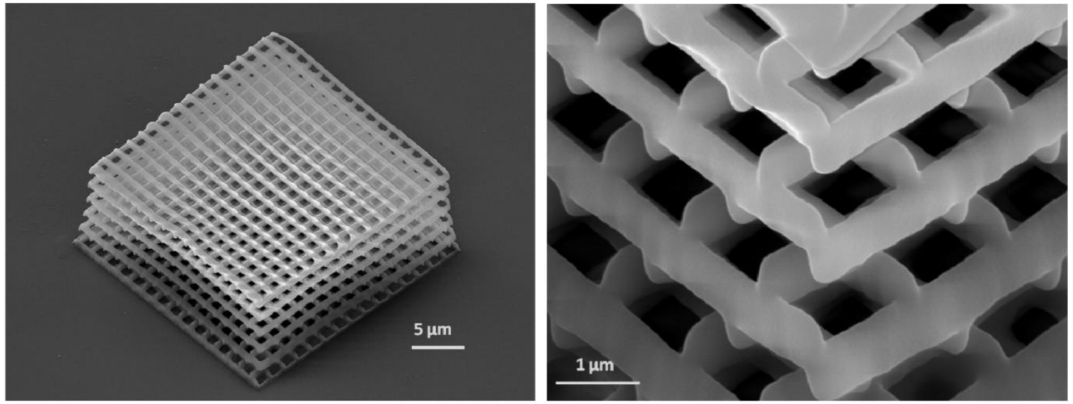
➢ **Next step: optical wavelength prototype realization through nanoscale techniques.**

Woodpile structure fabrication

- **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)**
  - By moving the focus of the beam three dimensionally, arbitrary 3D structures can be written into the volume of the material.



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Thank you!

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