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Copropagating schemes for dielectric laser accelerators

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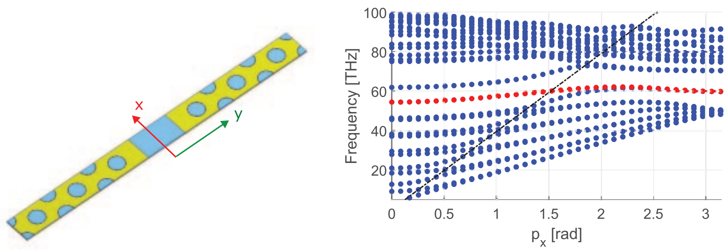
Summary. — Proof of principle electrons laser acceleration experiments, carried out by several groups, have demonstrated accelerating gradients larger than 200 MeV/m. However, the adopted configurations (free space coupled gratings, dual pillar, phase reset devices) cannot be easily scaled in length, because they require a transversely incident laser light, impinging laterally along the whole interaction dielectric structure. In this paper, extended interaction structures with collinear propagation of the accelerating electromagnetic field and the particles to be accelerated are described: both 2D and 3D photonic-crystals-based structures and slot hollow-core waveguides are compared in terms of accelerating gradient and characteristic interaction impedance, a fundamental quality parameter for Dielectric Laser Accelerators (DLAs).

1. – Introduction and motivation

The advancements in the fields of laser technology and dielectric Photonic Crystals (PhCs) optical waveguides design and construction have been driving a growing interest in Dielectric Laser Accelerators microstructures [1]. Thanks to the low ohmic-losses and the higher breakdown thresholds of the dielectrics with respect to the conventional metallic RF Linear Accelerators, the DLAs show a significant improvement of the acceleration gradient, up to the GV/m regime. Furthermore, optical-wavelength scaled size could lead to orders of magnitude fabrication costs reduction. Hollow-core, PhC-based waveguides [2] represent a suitable platform to develop DLAs. Several PhCs can be employed in order to obtain waveguide- or cavity-based accelerating structures. In this paper, we



(a) (b)

Fig. 1. – (a) 2D triangular lattice waveguide supercell; (b) projected band diagram along the accelerating x-axis. The TM_{01}-like mode, highlighted in red, is synchronous with the particles at $\lambda = 5\,\mu$m ($f_0 = 60\,$THz), where the curve crosses the speed of light line (dash-dotted black curve).

focus on the 2D triangular lattice and on the 3D woodpile waveguides, suited for relativistic particles and operating at wavelength $\lambda = 5\,\mu$m. We also present a dielectric accelerating structure, the slot waveguide, appropriate for sub-relativistic particles.

2. – Dielectric waveguides

2·1. *2D triangular lattice-based accelerating waveguide*. – The proposed waveguide, whose supercell is shown in fig. 1(a), is based on a 2D triangular lattice PhC, composed of periodically arranged vacuum holes of radius $r = 0.3d$, where d is the lattice constant (distance between two adjacent vacuum holes center) equal to $1.207\,\mu$m, on an alumina slab ($\epsilon_r = 9.7$). The structure operating wavelength, in our case $\lambda = 5\,\mu$m, leads to the choice of structure dimensions. The central vacuum channel, called "defect", has been tuned in order to support an accelerating mode, appropriate for acceleration, synchronous with the relativistic beam at the operating frequency of 60 THz, as seen in the projected band diagram of fig. 1(b). The accelerating mode presents a constant longitudinal component of the electric field and negligible transverse field components, as required for efficient particle acceleration.

2·2. *Slot waveguide*. – The slot waveguide, visible in fig. 2(a), is a dielectric structure employed for sub-relativistic electron acceleration: it supports a longitudinal accelerating field whose phase velocity can be tuned in order to maintain the synchronism with the accelerated electrons as they gain velocity. The structure has a constant section: it consists of two silicon "rib" waveguides of width $a = 0.59\,\mu$m and height $a = 0.22\,\mu$m supported by a SiO_2 substrate, separated by a hollow-core channel of width $d = 0.2\,\mu$m. Sizes are fixed by the operating wavelength (here $\lambda = 2\,\mu$m) and by the sub-relativistic regime: here we have normalized velocity $\beta = v/c \simeq 0.5$, v being the particle velocity. The operating mode profile, whose components are shown in fig. 2(b), presents a large on axis ($x = 0$) electric field longitudinal component and negligible transverse field components, as required for efficient particle acceleration. Further structure details are found in [3].

2·3. *3D woodpile mode launcher*. – The woodpile structure is based on a 3D photonic crystal lattice which consists of a combination of high-index dielectric bricks (silicon with $\epsilon_r = 11$ in our work), disposed in a periodic configuration as shown in fig. 3(a). The

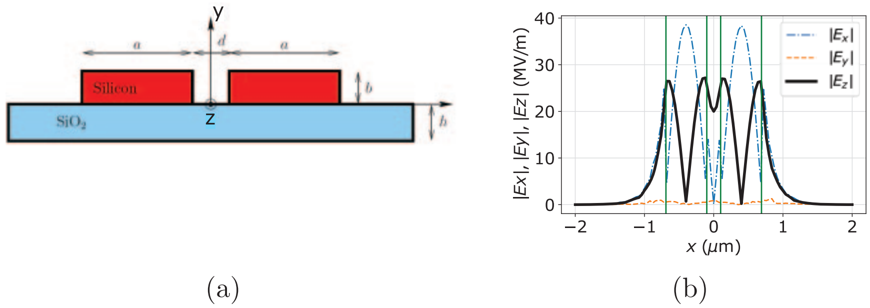


Fig. 2. – (a) Slot waveguide cross-section. (b) Electric field components $|E_x|$, $|E_y|$, $|E_z|$ along x (at $y = b/2$). On waveguide axis ($x = 0$), the longitudinal accelerating field component, $|E_z|$, is large with respect to the transversal ones, $|E_x|$ and $|E_y|$.

fundamental dimensions w, h and d, which represent the brick width, height and spacing between adjacent brick centers, are highlighted. The presented woodpile coupler operates at the wavelength of $\lambda_0 = 5\,\mu$m ($f_0 \simeq 60\,$THz) and the design procedure can be found in [4, 5]. The structure has been tuned in order to maximize the I/O wave transmission and, at the same time, optimize the efficiency of the input TE_{10} to the accelerating TM_{01} mode conversion. Figure 3(b) shows the electric field components along the longitudinal structure axis for a length of $L \simeq 31\,\mu$m and for input power of 250 W: the field presents a strong longitudinal component $|E_z|$, while the transversal components, $|E_x|$ and $|E_y|$, are almost equal to zero, as in the case of a TM_{01}-like accelerating mode.

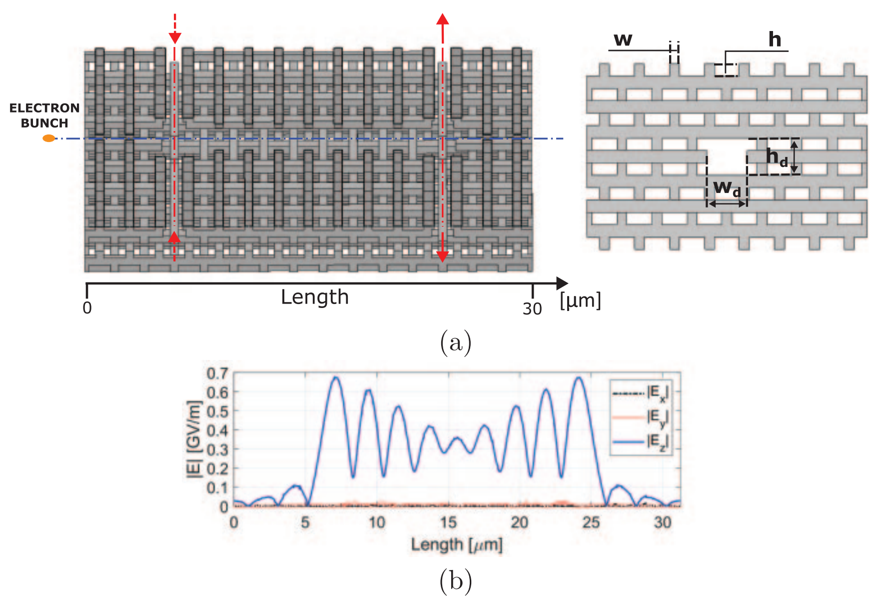


Fig. 3. – (a) Vertical (left) and front (right) cuts of the woodpile coupler. Input and output waveguide axes are indicated with red lines, while the accelerating waveguide axis is highlighted with a blue line. (b) Electric field component along the structure axis for an input power $P_{\text{inj}} = 250\,$W.

TABLE I. – Z_c *and* E_0 *values for the three presented dielectric accelerating structures, when* $P_{\rm inj} = 250$ *W and* $\lambda_0 = 5\,\mu$m *or* $\lambda_0 = 2\,\mu$m.

Structure ($\beta = v/c$, λ_0)	Z_c	E_0
2D waveguide ($\beta = 1$, $\lambda_0 = 5\,\mu$m)	37.73 [Ωm]	19.42 [MV/m]
Slot waveguide ($\beta = 0.5$, $\lambda_0 = 2\,\mu$m)	1600 [Ω]	0.3162 [GV/m]
Slot waveguide ($\beta = 0.5$, $\lambda_0 = 5\,\mu$m)	1600 [Ω]	0.1265 [GV/m]
3D woodpile mode launcher ($\beta = 1$, $\lambda_0 = 5\,\mu$m)	11400 [Ω]	0.3376 [GV/m]

3. – Accelerating gradient comparison

The structures have been compared in terms of on-axis accelerating gradient, defined as $E_0 = 1/L \int_0^L E(z)\mathrm{d}z$, where L is the channel length and $E(z)$ the on-axis electric field. We also compare the interaction impedance, a figure of merit defined as $Z_c = (E_0\lambda_0)^2/P_{\rm inj}$ [Ω], $P_{\rm inj}$ being the injected power. Table I reports the E_0 value for the three considered structures, for $\lambda_0 = 5\,\mu$m and $P_{\rm inj} = 250$ W. As an example, considering the woodpile structure, to obtain a final energy of 100 MeV, an accelerating channel length of 29 cm is required, leading to an extremely compact accelerator.

4. – Conclusion and perspectives

In this paper, we presented the design of three dielectric accelerating structures, based on 2D and 3D PhCs, for relativistic and sub-relativistic electron acceleration, that have been compared in terms of accelerating gradient: a clear performance advantage of the woodpile structure is evident at $\lambda_0 = 5\,\mu$m. It is clear that the 2D structure can be employed only with almost flat beams due to its small transversal size, while the 3D woodpile presents a wider application range. These devices could represent crucial components for the future tabletop DLAs. Furthermore, to accelerate particles from sub-relativistic to relativistic regimes, a cascade of different structures could be employed.

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