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NUMERICAL SIMULATION AND BEAM-DYNAMICS STUDY OF A HOLLOW-CORE WOODPILE COUPLER FOR DIELECTRIC LASER ACCELERATORS

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Abstract

Hollow core dielectric microstructures powered by lasers represent a new and promising area of accelerator research thanks to the higher damage threshold and accelerating gradients with respect to metals at optical wavelengths. In this paper we present the design of a dielectric Electromagnetic Band Gap (EBG) mode converter for high-power coupling of the accelerating mode in Dielectric Laser Accelerators (DLAs). The design is wavelength-independent, and here we propose an implementation operating at 90.505 GHz (wavelength 3.3 mm) based on a silicon woodpile structure. The coupler is composed by two perpendicularly coupled hollow-core waveguides: a TE-like mode waveguide (excited from RF/laser power) and a TM-like mode accelerating waveguide. The structure has been numerically designed and optimized, presenting Insertion Losses (IL) < 0.3 dB and an efficient mode conversion in the operating bandwidth. The properties and effectiveness of the confined accelerating mode have been optimized in order to derive the needed accelerating gradient. The simulated electric field has been used as input for Astra beam-dynamics simulations in order to compute the beam properties.

INTRODUCTION AND MOTIVATION

The latest years advancements in the fields of laser technology and the latest achievements in the design of dielectric Photonic-Crystal devices 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 (in the GV/m regime), leading also to scaled size devices and thus to orders of magnitude costs reduction with respect to the RF metallic accelerating structures [2]. For these reasons, several periodic structures have been proposed for laser-driven acceleration: photonic bandgap (PBG) fibers [3], side-coupled non-co-linear structures [4], 3D woodpile geometries [5], metamaterials-based optical dielectric accelerators [6]. Among these structures, we chose the woodpile since it exhibits a fully 3D frequency band-gap and because of its versatility that allows a simple optimization of the e. m. performances.

Hereinafter, a silicon Electromagnetic Bandgap (EBG) woodpile hollow-core waveguide structure side-coupler (or mode launcher-converter) design is presented. The full device is visible in Fig. 1(a). The TE_{10}-mode wave is injected into a metallic waveguide which splits into two branches that arrives to the woodpile mode converter section. Here the two waves are converted into the fundamental accelerating TM_{01}-like mode, which propagates along the hollow-core central accelerating waveguide (beam channel). When the wave reaches the end of the accelerating waveguide, it is back-converted into two waves which are picked-up by a second mode converter and driven out of the structure. This mode launcher design finds strong analogies with the travelling wave ones used for metallic LINACs where the input coupler, consisting of one or more rectangular waveguides, is realized by one (or more) slot that connects to the coupling cell [7–9].

HOLLOW-CORE WOODPILE COUPLER DESIGN

The woodpile structure is based on the 3D photonic crystal lattice which consists of a combination of high-index dielectric bricks (silicon with $\epsilon_r = 11$ in our work) immersed in vacuum background, stacked layer-by-layer, each layer rotated 90° with respect to the layer below and offset half a lattice period from the layer $2h$ below [10], as shown in Fig. 1(a). The structure has fundamental dimensions w, h, and d which represent the brick width, height and spacing between adjacent brick centers (the so called PhC period). As already recalled in electromagnetism, there are simple relationships between problems that differ for a contraction or an expansion [10, p. 20] and the woodpile electromagnetic design can be scaled to any desired working frequency by choosing the appropriate structure period d: the other dimensions are given in relation to d and are chosen in simulation with the objective of band-gap maximization.

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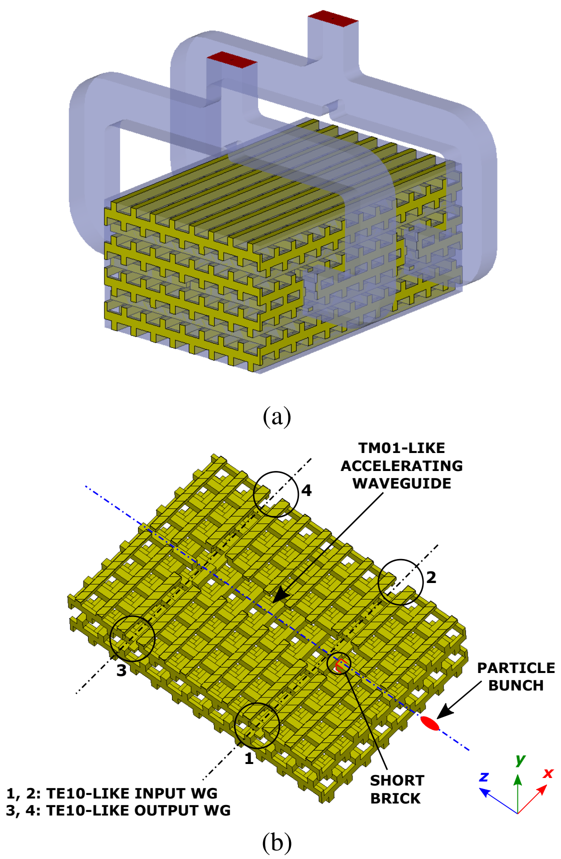

Figure 1: (a) 3D model of the presented EBG woodpile coupler with the I/O waveguides. The wave, injected into the launch metallic rectangular waveguide, highlighted in red, splits into two branches in order and enters the woodpile structure. An equivalent reverse procedure is employed to pick-up the wave that exits the dielectric coupler. (b) Structure slice in the xz plane. It is composed of a mode converter (from TE_{10}-like to TM_{01}-like mode) and a hollow-core waveguide supporting a TM_{01}-like mode that propagates along the same path of the particle bunch, accelerating it as the two synchronously travel along the channel (z direction). One of the two bricks composing the short wall of the mode converter is also highlighted.

The presented woodpile coupler operates at the wavelength of 3.3 mm ($f_0 \simeq 90.505$ GHz) and the design procedure is described in the following. As a first step, the band diagram (normalized frequency vs. normalized wavevectors) of the woodpile structure is calculated by using the MIT Photonics Band (MPB) software [11]. In order to obtain the maximum band-gap, the normalized brick dimensions $w = 0.2\sqrt{2}/d$, $h = 0.25\sqrt{2}/d$ have been used. The band-gap can be centered around the desired working frequency by choosing the period d through the expression $f_{[GHz]} \approx f_{norm}c/d$. By choosing $d = 1.38$ mm, we obtain a band-gap centered at around 85 GHz with fundamental woodpile dimensions $w = 0.39$ mm, $h = 0.49$ mm. Subsequently, a hollow core accelerating waveguide is obtained by removing a specific amount of dielectric material from the structure, in the region where the beam will propagate [12, 13]. The accelerating waveguide, whose projected band diagram is shown in Fig. 2, has been tuned in order to support a confined TM_{01}-like mode and has transversal dimensions $w_d = 1.61$ mm and $h_d = 1.46$ mm (xy plane). Finally, we proceeded to create the mode-converter sections (back-to-back configuration): it consists of two TE_{10}-like hollow-core waveguides, side-coupled with the beam channel, whose waves are combined through the use of two properly tuned dielectric short bricks for an efficient coupling of the accelerating TM_{01}-like mode. Figure 1(b) shows the dielectric structure along a xz plane slice: the I/O dielectric waveguide axes are highlighted with black dash-dotted lines, while the accelerating waveguide axis is highlighted with blue dash-dotted line. The travelling wave is picked-up at the structure's end by a second mode converter in order to be re-injected at the input port.

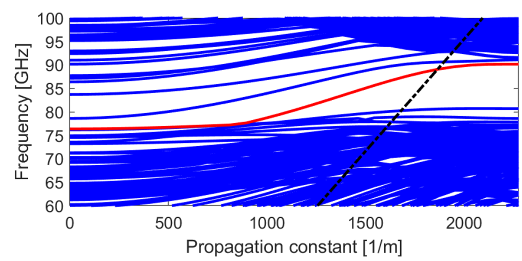

Figure 2: Projected band diagram along the accelerating hollow-core waveguide axis (z axis). The light line $\omega = ck_z$ (black dash-dotted curve) intercepts the guided TM_{01}-like mode at the frequency of 90.505 GHz.

NUMERICAL RESULTS

The structure has been tuned in order to maximize the back-to-back wave transmission and the quality of the TE_{10}-to-TM_{01} mode conversion. Figure 3(a) shows the S-parameters: the operational bandwidth at $IL = 0.3$ dB is 90.46-90.55 GHz and the mode conversion is maximum at $f_0 = 90.505$ GHz. Figure 3(b) shows the electric field components along the accelerating waveguide axis at the frequency of 90.505 GHz, for a length of $3d = 4.14$ mm and with 1 W input power: it can be seen that the field presents a strong longitudinal component $|E_z|$ while the transversal components, $|E_x|$ and $|E_y|$, are almost equal to zero, thus confirming the correct TM_{01}-like mode conversion.

Finally, in Fig. 4 it can be seen that the TM_{01}-like mode possesses phase velocity equal to the speed of light at the operating frequency and along the accelerating hollow-core waveguide, enabling the presented TW structure for relativistic electrons acceleration.

BEAM-DYNAMICS STUDY

The possibility to power a ~ 90.505 GHz dielectric structure is appealing from the beam dynamics point of view, because the millimetric acceleration bucket size, and

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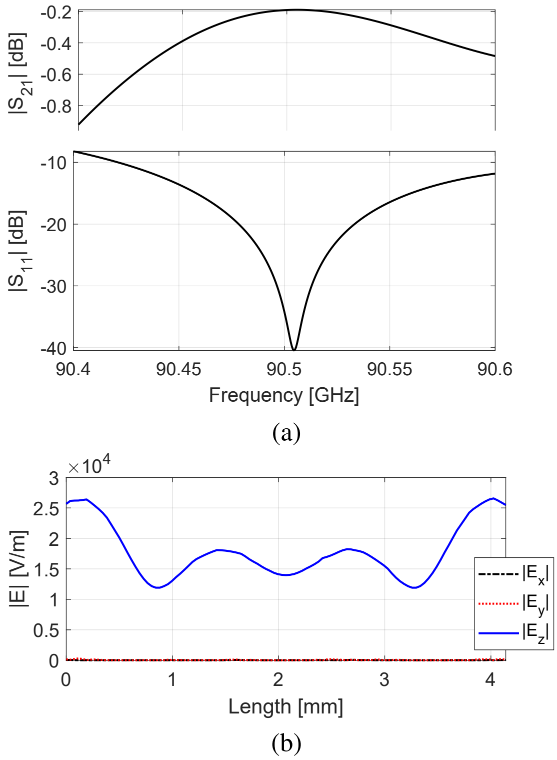

Figure 3: (a) $|S_{21}|$ (top) and $|S_{11}|$ (bottom) for the presented EBG woodpile coupler; (b) electric field components along the accelerating waveguide axis, at $f_0 = 90.505$ GHz, for a length of $3d = 4.14$ mm.

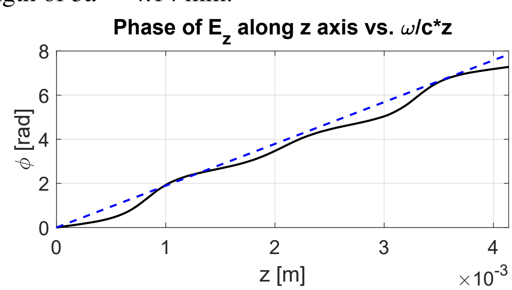

Figure 4: Phase plot of the guided TM_{01}-like mode longitudinal (accelerating) component $|E_z|$ (black line), vs. $k_z = \frac{\omega}{c}$ (blue dashed line), at $f_0 = 90.505$ GHz and for the entire accelerating waveguide length. It can be seen that the guided mode travels at the speed of light, thus the structure is suitable for relativistic electrons acceleration.

the transverse dimension size (hundreds microns), give the possibility to use a photoinjector to inject electron bunches in these kind of structures; photinjectors are typically used in the field of high brightness electron LINACs. Considering this injection scheme, we made preliminary simulations by using the tracking code ASTRA [14], which is an ad hoc tool to simulate the whole line: the photoinjector (with the laser driven photon electron bunch extraction) and the woodpile dielectric structure. The beamline is the following: a 2.856 GHz 1.6 cell photoinjector, with a peak acceleration field of 60 MV/m, able to accelerate an electron bunch at 2.8 MeV, followed by a solenoid to focus the bunch at ~ 1.5 m far from the cathode. A 10 pC electron bunch is extracted from the photocathode driven by a 7 ps flattop laser pulse (1 ps of rise times) focused at 90 µm (rms). Bunch parameters at the solenoid focal spot are: an envelope less than 100 um, a length of ~ 1.7 mm and a stable normalized emittance of ~ 140 nm, which are good to inject into the 90.505 GHz woodpile structure. The latter has been simulated with ASTRA, considering a semi-analytical acceleration field (in cylindrical symmetry) with a 200 MV/m $|E_z|$ peak amplitude. The results show that being the bunch quite long it sees the whole wave acceleration phase and by the initial slipping caused by a not fully relativistic energy, there is a distribution rotation into the longitudinal phase space, where the central part of the bunch overlaps the bunch head. This effect seems to degrade the emittance, but computing the normalized projected emittance value of ~ 50% of the particles distribution on the wave crest it is still 140 nm, while the slice emittance never exceeds the value of 180 nm. In about 10 mm the whole bunch gains about 900 keV, while on the crest ~ 50% of the distribution gains more then 3 MeV. The next step we are working on is to import into ASTRA a full 3D map, extracted from the numerical simulation, in the way to consider the inhomogeneity of the transverse fields.

CONCLUSION AND PERSPECTIVES

In this paper we presented the design of a compact dielectric coupler to be employed for future DLAs setups, working at the wavelength of 3.3 mm and based on the woodpile PhC. The hollow-core structure allows to convert an input TE_{10}-like mode, coming from two input waveguides, into a TM_{01}-like mode, accelerating the electron bunch injected into the structure with phase velocity synchronous with the EM phase. The structure has been tuned through the use of e. m. commercial simulators, showing very good S-parameters performances inside the operational bandwidth centered at the frequency of 90.505 GHz, around which an efficient mode conversion is also observed. The presented coupler design is wavelength-independent and could represents a crucial component for the future tabletop DLAs operating at optical wavelengths. Preliminary beam dynamics simulations have shown that a ~ 90 GHz acceleration cavity can be injected by a conventional photoinjector. Further studies photoinjector based will consider an optimized beamline to generate shorter bunches at the cavity entrance to decrease the energy spread and to better control the distribution longitudinal phase space rotation.

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