Design of a multi-channel photonic crystal
dielectric laser accelerator

Zhixin Zhao¹, Dylan S. Black¹, R. Joel England², Tyler W. Hughes¹, Yu Miao¹, Olav Solgaard³, Robert L. Byer¹, and Shanhui Fan¹*

¹Ginzton Laboratory, 348 Via Pueblo, Stanford University, CA, 94305, USA
²SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA
³shanhai@stanford.edu

Abstract: We propose a photonic crystal architecture for a dielectric laser accelerator that enables simultaneous acceleration of multiple electron beams. To achieve this, the band structure condition is discussed. © 2020 The Author(s)

Dielectric laser accelerators (DLAs) have the potential to provide acceleration gradient one order of magnitude higher than conventional radio-frequency accelerators, due to the high damage threshold of dielectric materials in the near-infrared. To promote the application of DLAs in both fundamental science and medical therapy, it is important to deliver high electron currents, which is a challenge for DLAs with a single sub-wavelength narrow channel (Fig. 1(a)). Therefore, we explore a photonic crystal DLA architecture that has multiple electron channels (Fig. 1(b)). Consistent with [1], we focus on silicon pillars and refer this design as a Multi-Input Multi-Output Silicon Accelerator (MIMOSA) [2].

We find that the essential characteristics of the MIMOSA are captured in the band structure and eigenmode properties of the underlying infinite photonic crystal. For simplicity, we study a two dimensional photonic crystal with a rectangular lattice (Fig. 1(c)), where the dielectric pillars extend uniformly in the y-direction, which is a valid approximation for pillar height larger than wavelength. In a two-dimensional photonic crystal, the fields can be decomposed into TE (nonzero \( E_y \), \( H_x \) and \( H_z \)) and TM (nonzero \( E_x \), \( E_z \) and \( H_y \)) polarization. Since only the TM polarization provides acceleration, we study only the TM polarization. We assume that the electrons travel along \( z \)-direction and are centered around \( x = 0 \) and the incident light propagates along the \( x \)-direction. Therefore, the incident laser can excite eigenmodes lying on \( kx \) direction in the reciprocal space (Fig. 1(d)). Furthermore, the mode at \( \Gamma \) point has the same phase in each unit cell. Thus, to ensure that the electron beams in different channels get the same acceleration, the mode at \( \Gamma \) point should be excited dominantly. Therefore, the frequency \( \omega \) of the eigenmode at \( \Gamma \) point should match the frequency \( \omega_0 \) of the incident light. In addition, the phase synchronization condition for DLA should be satisfied,

\[
\omega(\Gamma) = \omega_0 = \beta \times 2\pi mc/L,
\]

where \( c \) is the speed of light, \( \beta = v/c \) where \( v \) is the speed of electron, \( L \) is the periodicity along \( z \)-direction, and \( m \) is the diffraction order (typically \( m = 1 \)).

Additionally, the unit cell of typical photonic crystals may have certain symmetries. In the demonstration shown in Fig. 1(c), the mirror-x and mirror-z symmetries of the unit cell require that the acceleration mode should also have certain symmetries. To accelerate the electron traveling along \( x = 0 \), the mode should be symmetric with respect to \( x = 0 \) (red dots in Fig. 1(e)). And to couple to plane waves propagating in \( x \)-direction, the mode should have odd mirror-z symmetry. In other words, the photonic crystal underlying the MIMOSA should support an eigenmode at normalized frequency (frequency normalized by \( c/L \)) \( \beta \) with odd mirror-z and even mirror-x symmetry, below we refer to such a mode as an acceleration mode. This condition on the symmetry of acceleration mode, together with Eq. (1), represents one of the main contributions of this study and is referred to as the band structure condition. It can be satisfied through tuning the geometrical parameters of the dielectric pillar.

Moreover, the figure of merit of the MIMOSA can also be derived from eigenmode analysis of the underlying photonic crystal. This “acceleration factor” \( g \) is the maximal acceleration gradient at the center of the electron channel divided by the maximal electric field inside the dielectric material [2]. From the field profile of the acceleration mode (Fig. 1(f)), which is computed for a structure that is infinitely periodic along the both the \( x \) and \( z \)-directions, we can calculate the acceleration factor, which turns out to be close to the acceleration factor of the MIMOSA, where the structure is finite along the \( x \)-direction.

We demonstrate the design of a MIMOSA for electron speed 0.5c (\( \beta = 0.5 \)) with rectangular silicon pillars and a central laser wavelength \( \lambda_0 = 2 \mu m \). The same design principles apply to other electron speeds, pillar shapes, dielectric material systems and laser wavelengths. By tuning the geometries (Fig. 1(c)), the photonic
Fig. 1. Schematic of a dual pillar DLA (a) and a multi-channel DLA (b) under dual laser drive. Electrons travel inside parallel channels along $z$-direction. (c) Unit cell of the photonic crystal (dashed red box) with rectangular pillar (length $2a = 0.6 \, \mu m$, width $2b = 1.72 \, \mu m$), channel width $2d = 0.4 \, \mu m$, and periodicity in $z$-direction $L = 1 \, \mu m$. (d) The reciprocal Brillouin zone. (e) Band structure of the TM mode. Big (small) black dots represent eigenmodes with odd (even) mirror-$z$ symmetry, and red (blue) dots represent eigenmodes with even (odd) mirror-$x$ symmetry. (f) Field profiles of the eigen modes at $\Gamma$ point with normalized frequency 0.500. Under dual laser drive (g), the field distribution in the MIMOSA is shown in (h) for $E$ field magnitude and in (i) for $E_z$, $E_x$, and $Z_0H_y$ components, where $Z_0$ is the free space impedance.

crystal supports an acceleration mode (Fig. 1(f)), at normalized frequency 0.5 (Fig. 1(e)), from which the inferred acceleration factor is $g = 0.51$.

To verify our design principles, we truncate the photonic crystal in the $x$-direction to specify a finite number of channels and perform a full wave simulation. For demonstration purpose, we limit the number of electron channels to $N = 3$. The field distributions are shown in Fig. 1(h-i), where the two driving plane waves are symmetric with respect to $x = 0$. The fields inside different electron channels are almost identical and strongly resemble the eigenmode shown in Fig. 1(f). From Fig. 1(h), we find that the largest $E$ field is inside the vacuum rather than inside the dielectric, which contributes to the high acceleration factor. The acceleration factors are 0.512, 0.494 and 0.512 in channels 1, 2, and 3 respectively. The small variance for force distributions in different channels holds better as the number of channels increases. The bandwidth of the 3-channel MIMOSA is 62 nm, corresponding to 95 fs pulse duration of a transform limited Gaussian pulse at 2 $\mu m$. With such a pulse and a fluence half of the damage fluence of silicon (0.17 J/cm$^2$), the predicted acceleration gradient can reach 0.56 GeV/m. As the number of electron channels increases, the bandwidth of the MIMOSA decreases and the corresponding pulse duration increases. We estimate that the corresponding pulse duration scales linearly with the number of channels as $\tau (fs) = 40.8 \times N - 54.4$ for large $N$.

Besides acceleration, the MIMOSA may also provide a platform to study and manipulate multiple e-beams, such as the interference of phase-locked e-beams, multi-beam ultra-fast diffraction, and coherent radiation generation. To summarize, our study opens new opportunities in dielectric laser accelerators and, in general, nanoscale electron manipulation with lasers.

References

1. Kenneth J Leedle, Dylan S Black, Yu Miao, Karel E Urbanek, Andrew Ceballos, Huiyang Deng, James S Harris, Olav Solgaard, and Robert L Byer. Phase-dependent laser acceleration of electrons with symmetrically driven silicon dual pillar gratings. Optics Letters, 43(9):2181–2184, 2018.

2. Zhexin Zhao, Dylan S. Black, R. Joel England, Tyler W. Hughes, Yu Miao, Olav Solgaard, Robert L. Byer, and Shanhui Fan. Design of a multi-channel photonic crystal dielectric laser accelerator. Physical Review Applied, submitted.