DESIGN OF A DIELECTRIC LASER ACCELERATOR STRUCTURE FOR LOW β CHARGED PARTICLES

S. Maru†, K. Sakaue, The University of Tokyo, Tokyo, Japan
D. Satoh, T. Shibuya, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan
M. Konrad, J. Litzel, P. Hommelhoff, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

Abstract

Dielectric laser acceleration (DLA) is a novel acceleration scheme using dielectric nanostructures with high damage thresholds for the laser electric field. In DLA, the typical structural period is determined by the product of β, the electron velocity normalized to the speed of light, and the laser wavelength λ At low β, the structural period becomes extremely small, making fabrication impractical and limiting the range of initial energies that can be accelerated. In fact, DLA has so far been demonstrated only for initial energies above approximately 10 keV. We design DLA structures that extend the range of initial kinetic energy that can be accelerated to lower energies. By setting the structural period to an odd multiple of $\beta\lambda$ and specifically employing a $3\beta\lambda$ structure in this work, the fabrication constraints associated with low initial energies can be improved. As a result, acceleration is driven by enhanced third-order Fourier components of the laser field generated during transmission through the pillars, rather than by the original incident laser component. In this paper, we will report on a pillar cross-sectional design capable of accelerating low-energy electrons (5 keV) based on acceleration simulations.

INTRODUCTION

Dielectric laser acceleration (DLA) is a method for accelerating charged particles using laser near-fields when dielectric microstructures are irradiated with laser pulses. Since visible and near-infrared lasers are employed as the driving source, the operating frequency is more than four orders of magnitude higher than those of conventional radio-frequency accelerators. In addition, the achievable accelerating gradient is determined by the damage threshold of the dielectric material and can reach the GV/m scale, e.g., 1.8 GV/m for SiO_2 [1]. Therefore, DLA enables compact accelerators with high accelerating gradients.

A schematic illustration of DLA is shown in Fig. 1. To maintain phase-synchronism between the laser field and electrons, the accelerating structure is designed as a dielectric periodic structure with a period L determined by the following condition:

$$L = m\beta\lambda \tag{1}$$

, where m is the spatial harmonic order of the diffraction modes generated by the laser field, β is the electron velocity normalized to the speed of light, and λ is the laser wavelength. The channel width is determined by the decay length of the laser near-field used for acceleration [2]. For visible and near-infrared (NIR) lasers, the channel width is typically on the order of several hundred nanometers.

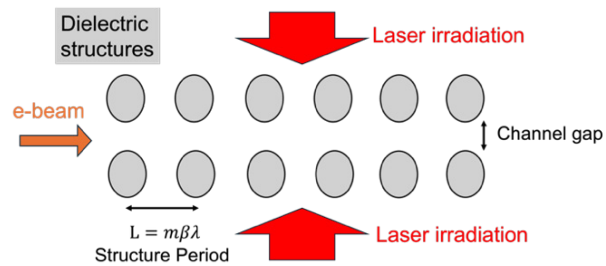

Figure 1: Schematic of dielectric laser acceleration.

On the other hand, one of the major challenges in DLA is the acceleration of electrons with very low initial energies, for which the fabrication of the accelerating structure becomes extremely difficult. This originates from the phase-matching condition for low-energy, non-relativistic electrons, which requires an excessively small structural period, thereby imposing a lower limit on the electron energy that can be accelerated. To address this issue, acceleration schemes based not on the incident laser field itself but on higher spatial harmonics of the laser field generated as the electrons pass through the pillar structure have been proposed, which have also been experimentally demonstrated using grating structures [3].

We aim to develop an ultra-compact accelerator based on DLA. To realize such a system, direct DLA of low-energy electrons without a pre-acceleration stage is required. Therefore, we investigate accelerating structures that enhance higher-order spatial harmonic components and design structures capable of accelerating electrons at lower energies.

DESIGN OF PILLAR STRUCTURES

In this study, the accelerating structure was designed to utilize the third spatial harmonic component, with the structural period set to $3\beta\lambda$. The $3\beta\lambda$ dual-pillar structure enables fabrication-compatible DLA structures for very low-energy electrons by avoiding the extremely small periods required in conventional $\beta\lambda$ -period structures.

Conventional dielectric laser accelerators generally utilize optical near-fields formed by the interference of laser fields irradiated onto both sides of the structure. However,

†senamaru@g.ecc.u-tokyo.ac.jp

this configuration requires precise control of the relative laser phase and incidence angle. To overcome this issue, structures employing a distributed Bragg reflector (DBR) as a reflective wall have been proposed [4]. In this work, we designed a single-sided illumination structure incorporating a DBR.

In conventional $\beta\lambda$ period structures, electrons are continuously accelerated by the fundamental spatial harmonic component of the near-field[5-7]. In contrast, for the $3\beta\lambda$ structure, only the third spatial harmonic component satisfies the phase-synchronism condition with the electrons. Therefore, the structure must be designed not only in terms of the field amplitude and phase but also with careful consideration of the electromagnetic field modes. Accordingly, electromagnetic simulations were performed using CST Studio Suite. The design parameters were set as follows: the initial kinetic energy of the injected electrons was 5 keV (β =0.139), and the center wavelength of the driving laser was 1950 nm. The input laser field was normalized such that the maximum electric-field amplitude reached 500 MV/m.

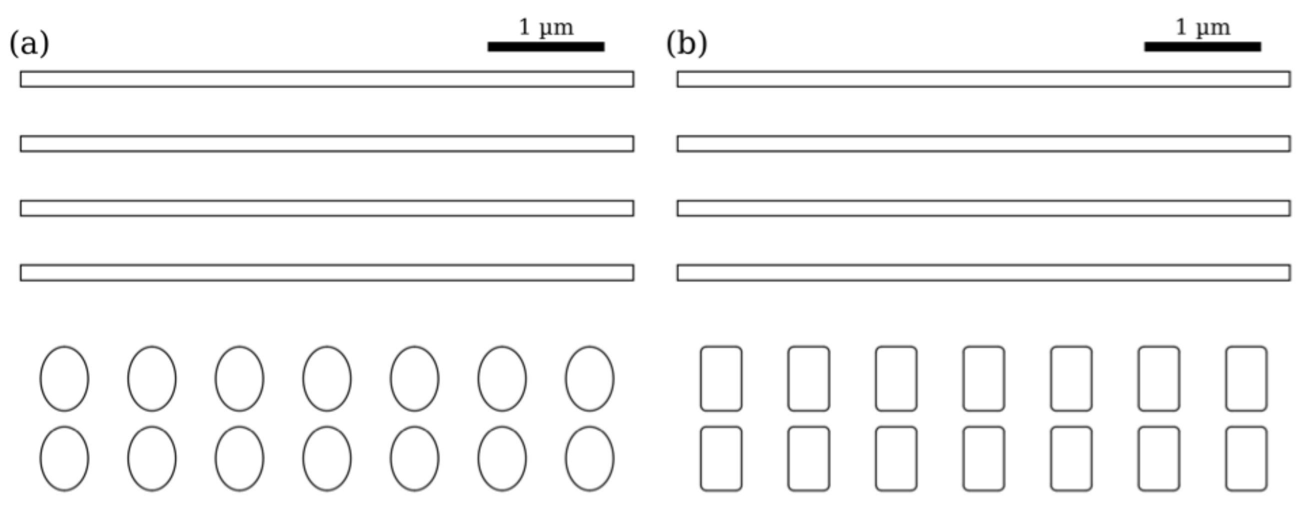

Figure 2: Designed single-sided illumination accelerating structures incorporating a DBR: (a) elliptical pillar structure and (b) rectangular pillar structure.

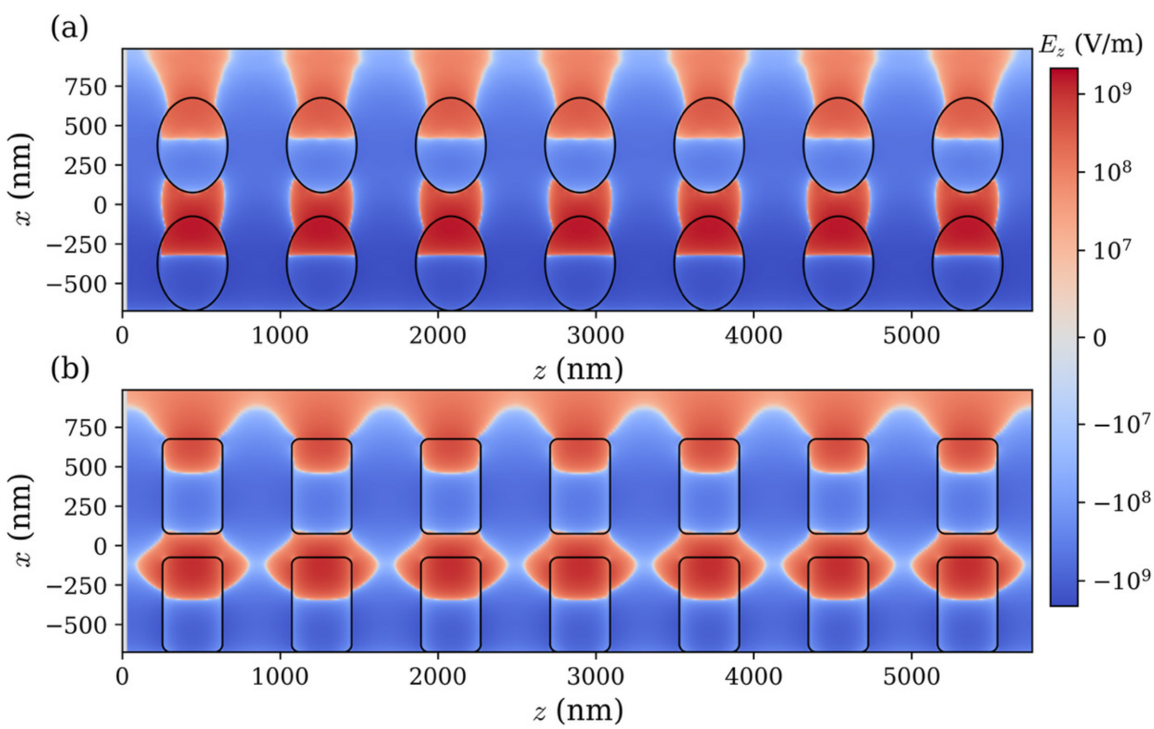

Figure 3: Simulated distribution of the z-component of the electric field under laser illumination at a wave-length of 1950 nm, with the laser propagating in the +x direction: (a) elliptical pillar structure and (b) rectangular pillar structure.

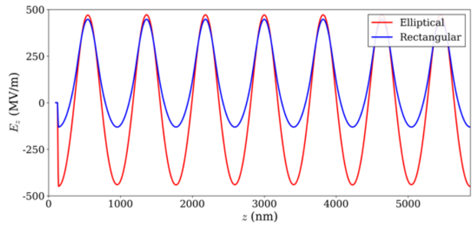

Figure 4: Line profile of the electric field E_z at the channel center ($x = 0$)

Fig. 2 shows the designed accelerating structures. While Fig. 2(a) shows a conventional pillar structure with an elliptical cross section commonly used in $\beta\lambda$ -period structures, Fig. 2(b) shows a structure designed with a rectangular pillar cross section to enhance higher spatial harmonic components. Both structures have a structural period of $3\beta\lambda$, a channel width of 150 nm, and a pillar height of 3 µm. The simulations were performed without a substrate.

Fig. 3 shows the distribution of the z-component of the electric field obtained by simulations under single-sided laser illumination. To evaluate the higher spatial harmonic components experienced by the electrons, Fourier analysis was performed using the line profile at the center of the channel gap as shown in Fig. 4. The first- and third-order spatial harmonic components were extracted from the resulting Fourier spectrum. The ratio of the third- to first-order components was found to be 0.34% for the elliptical pillar structure and 2.1% for the rectangular pillar structure.

ACCELERATION SIMULATION

Using the electromagnetic field data obtained from the field simulations, particle-in-cell (PIC) simulations were performed using CST Studio Suite. The initial kinetic energy of the electrons was set to 5 keV, and the electrons were injected parallel to the z-axis at a height of 1.5 μm. The simulated energy evolution of the electron with the maximum net energy gain is shown in Fig. 5.

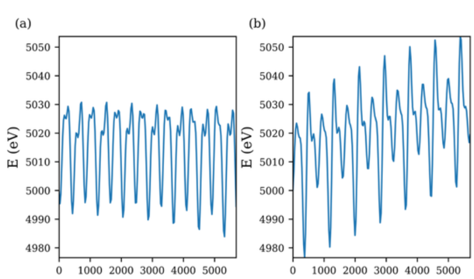

Figure 5: Energy evolution of an electron at the phase of maximum net energy gain: (a) elliptical pillar structure and (b) rectangular pillar structure.

The elliptical pillar structure exhibited no significant net energy gain, whereas the rectangular pillar structure achieved an accelerating gradient of 3.2 MeV/m. These results demonstrate that, unlike conventional acceleration driven by the fundamental spatial harmonic component of the near field, the rectangular pillar structure is effective for enhancing higher spatial harmonic acceleration in the $3\beta\lambda$ structure.

CONCLUSION

To realize acceleration at low electron energies, we designed and simulated pillar structures with a structural period of $3\beta\lambda$. The rectangular pillar geometry enhanced the third spatial harmonic component by more than a factor of six compared with the elliptical design, enabling electron acceleration at 5 keV while avoiding the extremely small structural periods required in conventional structures.

ACKNOWLEDGEMENT

This work was supported by the MEXT Development of Key Element Technologies to Improve the Performance of Future Accelerators Program, Japan, Grant Number JPMXP1423812204, and JSPS KAKENHI Grant Number 26H02038.

REFERENCES

[1] D. Cesar *et al*., "High-field nonlinear optical response in a dielectric laser accelerator", *Commun. Phys*., vol. 1, pp. 1–8, 2018. doi:10.1038/s42005-018-0047-y

[2] J. Breuer and P. Hommelhoff, "Laser-based acceleration of nonrelativistic electrons at a dielectric structure", *Phys. Rev. Lett*., vol. 111, p. 134803, 2013. doi:10.1103/PhysRevLett.111.134803

[3] J. McNeur *et al.*, "A miniaturized electron source based on dielectric laser accelerator operation at higher spatial harmonics and a nanotip photoemitter", *J. Phys. B*: *At. Mol. Opt. Phys*., vol. 49, p. 034006, 2016. doi:10.1088/0953-4075/49/3/034006

[4] P. Yousefi *et al*., "Dielectric laser electron acceleration in a dual pillar grating with a distributed Bragg reflector", *Opt. Lett*., vol. 44, pp. 1520–1523, 2019. doi:10.1364/OL.44.001520

[5] D. S. Black *et al*., "Net acceleration and direct measurement of attosecond electron pulses in a silicon dielectric laser accelerator", *Phys. Rev. Lett.,* vol. 123, p. 264802, 2019. doi:10.1103/PhysRevLett.123.264802

[6] T. Chlouba *et al*., "Coherent nanophotonic electron accelerator", *Nature*, vol. 622, pp. 476–480, 2023. doi:10.1038/s41586-023-06602-7

[7] L. Brückner *et al*., "Mid-infrared dielectric laser acceleration in a silicon dual pillar structure", *Opt. Express*, vol. 32, pp. 28348–28355, 2024. doi:10.1364/OE.531071