Optimized Silicon Asymmetric Dual-Pillar Grating for Dielectric Laser Acceleration of Subrelativistic Electrons with Enhanced Accelerating Gradient

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Dielectric laser accelerator has great potential for the miniaturization of particle accelerators. We present results of the numerical investigation of a silicon dual-pillar grating structure with a high accelerating gradient for subrelativistic electrons. An asymmetric configuration is utilized to generate an accelerating mode with lower skew. Driven by a 1550 nm laser with a peak fluence of 20 mJ/cm² and a pulse length of 100 fs, the structure could achieve a maximum gradient of 0.42 GV/m for 50 keV electrons.

Key Words: Dielectric laser acceleration, Grating structure, Subrelativistic electrons, High accelerating gradient

1. Introduction

Dielectric laser accelerators (DLAs) have attracted increasing interest in the recent years for their high accelerating gradients enabled by the high damage thresholds of dielectric materials in optical region.1-4) They also have the capability to deliver particle beams with a nanometer size and an attosecond pulse length.5,6) Recently, by leveraging the well-developed industrial fabrication capabilities and the commercially available high-power lasers, accelerating gradient of 690 MV/m has been achieved with fused silica dual-grating DLA for relativistic electrons, and accelerating gradient of 370 MV/m has been obtained with silicon dual-pillar DLA for nonrelativistic electrons.7-11)

Described here is a silicon asymmetric dual-pillar DLA structure for the acceleration of subrelativistic electrons. The structure is a modification from the dual-pillar structure experimentally demonstrated by Leedle, et al.11), but with a longitudinal offset between the two rows of pillars. The longitudinal offset enables an accelerating mode with lower skew and higher accelerating gradient in the channel.12,13) The results show that electrons could experience a rather uniform accelerating field in the structure.

2. Geometry and Work Principle

Figure 1 shows the schematic view of the asymmetric dual-pillar grating structure that consists of two rows of pillars separated by a vacuum channel and its work principle. The grating period is \( \lambda_g \), the pillar length \( L_p \), the pillar width \( W_p \), the pillar height \( H_p \), the width of vacuum channel gap \( G \), and the longitudinal offset between the two rows of pillars \( \Delta \). Electrons travel along the longitudinal direction (Z direction) in the channel, and the laser is incident from below in the Y direction at normal incidence to the grating surface, with electric field polarized along the electron beam trajectory.

The silicon material used in this structure promises a comparable or higher accelerating gradient due to its higher refractive index than SiO₂ material despite the lower damage thresh-
celer with the waveguides and other components.

At the first single grating with one row of pillars, the diffractive effect of the incident wave from below excites a series of spatial harmonics, with wave vectors $k_0 = n_k \omega$, in which the grating vector $k_1 = 2 \pi \lambda_0 \omega$, and the order number $n = 0, 1, 2, \cdots$.

Therefore, the nth ($n \neq 0$) spatial harmonic propagates in the Z direction with a phase velocity $v_n = \omega / k_n = c \lambda_n / n_k$, with $\lambda_n$ the laser wavelength, $\omega$ the angular velocity and $c$ the speed of light. Continuous acceleration of electrons requires the phase velocity of one spatial harmonic to be equal to the electron velocity $v$, yielding the synchronicity condition between the electron and the spatial harmonic $^{(1)}$:

$$\beta = \frac{\lambda_n}{n_k}$$

with $\beta$ the electron velocity $v$ normalized to the speed of light $c$. The dispersion relation $k_n^2 = k_0^2 + k_y^2$ of the spatial harmonics with $k_0 = \omega / c$ the wave vector in vacuum and $k_0 = 0$ for 2-dimensional geometry, shows that the values of $k^2$ are negative. The set of imaginary values of $k_n$ indicate that the fields take the form $e^{\pm i \omega t - k_y y} \sinh(k_y y)$ and fall off exponentially with an increasing distance from the pillar surface in Y direction, in which $\Gamma$ is the decay constant that defines the non-radiative waves existing in the near field zone $^{(1)}$:

$$\Gamma = \frac{i}{k_0} = \frac{i}{\sqrt{k_0^2 - k_n^2}} = \frac{\beta \lambda_n}{2 \pi}$$

where $\gamma = (1 - \beta^2)^{-1}$ is the Lorentz factor.

For the dual-pillar structure illuminated by one laser, the modes at the second single grating are excited by the transmitted plane wave from the first single grating. The superposition of the two evanescent modes from each single grating could form an accelerating mode with the form of $\cosh(k_y y)$ or $\sinh(k_y y)$ across the channel, depending on the phase delay between the two evanescent modes. The cosh mode has a rather uniform accelerating field around the axis of the accelerating mode across the channel, which is desirable for an accelerator. To produce such a cosh mode, a longitudinal offset $\Delta$ between the two single gratings is needed to make sure the evanescent modes from each single grating are in phase, so the electron beam is not longitudinally distorted. In this case, electrons enter at the same optimal start phase could experience the maximum acceleration across the channel.

3. Simulation with CST

To study the field distribution and determine the optimal dimensions of the grating structure, we use the well-established CST software. The two rows of pillars can be treated as a 2-dimensional structure as shown in Fig. 1 (b) since the effect of the slab at the bottom of the pillars as shown in Fig. 1 (a) can be neglected with a pillar height larger than the diameter at the focus of the laser pulse. Only one period of structure is modelled, as shown by the rectangular box in dashed line in Fig. 1 (b), with periodic boundary conditions applied in Z direction, and open boundary conditions applied in Y direction. The mesh size is $\lambda_0 / 80$. The simulation method is verified with the reported simulation results from the literature $^{(14)}$.

In the simulation, the accelerating gradient $G_0$ and the deflecting gradient $G_2$ are defined as the average longitudinal accelerating and transverse deflecting fields experienced by electrons over one period of the grating, respectively. One important metric is the accelerating gradient normalized to the incident electric field $E_i$, which can be written as $\eta_{ac} = G_0 / E_i$. If we take into account the damage threshold of the material which limits the achievable highest gradient, the enhancement factor $\eta_{enh} = E_{max} / E_i$, which quantify the structure’s ability to enhance the input field $E_i$, should be considered, with $E_{max}$ the maximum field in the material. In order to obtain the highest gradient, the figure of merit is the ratio of accelerating gradient to the maximum field in the material, which is known as the acceleration factor $f_\eta = G / E_{max}$. In the simulation, the dual-pillar structure is optimized in two steps: the first step is to optimize the pillar shape of a single grating with one row of pillars to generate an accelerating mode with high amplitude, and the second is to optimize the longitudinal offset $\Delta$ to make sure the relative phase between the two evanescent modes is zero.

We assume the structure is driven by a laser with wavelength $\lambda_0 = 1550$ nm. The initial energy of electrons is 50 keV, with $\beta = 0.41$. To satisfy the synchronicity condition as shown by eq. (1) for the first harmonic, the grating period is $\lambda_0 = 640$ nm. To enable the uniaxial acceleration of electrons, the pillars should serve as a phase mask to add an odd times of $\pi$ phase shift with respect to the adjacent vacuum space on the electric field along the electron beam axis so that the accelerating field works like a standing wave, yielding the requirement for pillar length $L_p$

$$L_p = \frac{m \lambda_0}{2 (n_0 - 1)}$$

with the refractive index $n_0$ and an odd number $m$. For the silicon material with $n_0 = 3.45$, the corresponding pillar length should be $L_p = 0.2 m \lambda_0$. We chose a narrow channel gap $G = 0.2 \lambda_0 = 310$ nm to make sure that we could obtain a high accelerating gradient at the channel center from the superposition of the evanescent modes at each single grating, considering that those evanescent modes decay exponentially with the increasing distance from the grating surface.

To optimize the pillar shape, we simulated a single grating with one row of pillars to study the effect of pillar length $L_p$ and pillar width $W_p$ on the acceleration factor $f_\eta$ and normalized accelerating gradient $\eta_{ac}$ for electrons at the optimal start phase at a distance of 155 nm above the single grating illuminated from below, with the results as shown in Fig. 2. Because of a bound of the pillar height $H_p \leq 1500$ nm set by the manufacturer, the laser beam waist radius $w_0$ in the Y direction is limited by $w_0 \leq H_p / 2 = 750$ nm. To make sure the electric field of the incident laser in the simulation area as shown by the rectangular box in dashed line in Fig. 1 (b) can be considered as parallel lights, the pillars should be located inside the Rayleigh length $z_R$ of the laser pulse, i.e. $z_R = \pi w_0 / \lambda_0 \leq L_p / 2$. Therefore, the pillar length is limited by $L_p \leq 4 w_0$. We chose $w_0 = 65 \lambda_0$ and $n_0 = 3.45 \lambda_0$. The accelerating factor reaches its maximum at $L_p = 0.2 \lambda_0$ and $W_p = 0.65 \lambda_0$. But it can be seen that with pillar length $L_p = 0.6 \lambda_0$ and pillar width $W_p = 0.5 \lambda_0$, the normalized accelerating gradient is much higher while the acceleration factor is comparable to its maximum, which means we can obtain a comparable maximum accelerating gradient with a much lower laser power. So here we chose the optimal pillar

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1. http://www.cst.com/
length $L_p$ and pillar width $W_p$ to be $0.6\lambda_p$ and $0.5\lambda_p$, respectively, with maximum acceleration factor $f_a = 0.09$ and normalized accelerating gradient $\varepsilon_a = 0.27$.

As shown in Fig. 3, for the single grating, the optimal accelerating start phase and optimal deflecting start phase stay unchanged with the increasing distance from the grating surface, with a difference of $\pi/2$. The maximum accelerating and deflecting gradients fall off exponentially from the grating surface with a decay constant $\Gamma = 112$ nm. It can be easily seen that for an electron beam with a finite transverse size, the skewed mode leads to a large energy spread and distortion.

For the dual-grating structure, by changing the longitudinal offset $\Delta$ the relative phase between the evanescent modes at the two gratings is shifted. If the evanescent modes are in phase, the overlay of the accelerating field results in a strong acceleration in the channel and a cosh mode is generated. If the two evanescent modes are out of phase, electrons at different $y$ positions have different optimal accelerating start phase and the electron beam is distorted. In our simulation, with a longitudinal offset $\Delta = 0.06\lambda_p$, the relative phase delay between the two evanescent modes becomes zero. The longitudinal electric field including all the spatial harmonics in the optimized dual-pillar grating structure is shown in Fig. 4 (a).

The electric field in the channel is efficiently modulated by the grating, with the maximum electric field in the grating material located at the corner of the pillar near the channel.

![Fig. 2](image1)

**Fig. 2** The dependences of the normalized accelerating gradient $\varepsilon_a$ and acceleration factor $f_a$ for electrons at the optimal start phase at a distance of 155 nm from the grating surface on the pillar length $L_p$ and pillar width $W_p$.

![Fig. 3](image2)

**Fig. 3** Maximum normalized accelerating gradient $\varepsilon_a$ (dash-dot line) and deflecting gradient $\varepsilon_d$ (solid line) in the vicinity of the single grating with optimized pillar shape, and the corresponding optimal accelerating start phase $\theta_a$ as well as the optimal deflecting start phase $\theta_d$ of electrons in the optical cycle, with the pillar surface located at $y = -155$ nm.

![Fig. 4](image3)

**Fig. 4** Field simulation results of the dual-pillar structure. (a) Longitudinal electric field distribution in the structure, including all harmonics. The grating period $\lambda_p = 640$ nm, the pillar length $L_p = 930$ nm, the pillar width $W_p = 320$ nm, the vacuum gap $G = 310$ nm and the longitudinal offset between the two rows of pillars $\Delta = 0.06\lambda_p$. (b) Optimal start phase for maximum acceleration $\theta_a$ with longitudinal offset $\Delta = 0.06\lambda_p$ (dotted line) and $\Delta = 0$ (dashed line) across the channel, and the normalized accelerating gradient $\varepsilon_a$ (dash-dot line) and normalized deflecting gradient $\varepsilon_d$ (solid line) at their optimal start phases with $\Delta = 0.06\lambda_p$. Position $y = 0$ nm is located at the center of the channel. (c) The effect of start phase $\theta$ on the normalized accelerating gradient $\varepsilon_a$ and normalized deflecting gradient $\varepsilon_d$ at $y = 0$ nm with $\Delta = 0.06\lambda_p$.
accelerating mode experience no deflection. If we neglect the dephasing, which is valid as the energy gain $\Delta E$ is well below the energy differences, the dependences of the maximum gradient and maximum energy gain on the fluence $F_{\text{in}}$ of a Gaussian laser pulse can be given by:

$$ G_{\text{in}} = \frac{2F_{\text{in}}}{\varepsilon_0 \varepsilon_r \tau_p} $$  \hspace{1cm} (4) \\

$$ \Delta E = G_{\text{in}} \sqrt{\frac{1}{w_z^2} + \frac{2 \ln(2)}{\beta c \tau_p}} $$  \hspace{1cm} (5) \\

with $\varepsilon_0$ the vacuum permittivity, $w_z$ the laser beam waist radius in the longitudinal direction, and $\tau_p$ the FWHM pulse length. The reported damage threshold of bulk silicon material $F_{\text{th}} = 0.19 \, \text{J/cm}^2$ requires an incident laser with fluence $F_{\text{in}} < F_{\text{th}} / \eta_{\text{max}}^2 = 20 \, \text{mJ/cm}^2$ so that the maximum electric field $E_{\text{max}}$ in the material doesn’t exceed the damage threshold field. In this case, assuming a laser pulse length $\tau_p = 100$ fs, the maximum achievable accelerating gradient on the axis of the accelerating mode is 0.42 GV/m. Assuming a laser beam waist radius in the longitudinal direction $w_z = 5 \, \mu m$, the maximum energy gain given by eq. (5) is 3.33 keV. For electrons travel close to the grating surface, a higher accelerating gradient and energy gain can be obtained. To accelerate the electrons to a higher energy, e.g. 1 MeV, a multi-stage DLA, in which the grating structure of each stage is optimized to maximize the accelerating gradient for different electron velocities, should be proposed.

4. Conclusion

We present results of the numerical study of a silicon asymmetric dual-pillar grating structure for the acceleration of 50 keV electrons driven by a 1550 nm laser. The structure is optimized with a relative longitudinal offset between the two rows of pillars to produce a coss accelerating mode with a maximum normalized accelerating gradient of 0.34 and a maximum acceleration factor of 0.11 on the axis of the mode. Considering the damage threshold of silicon material, a maximum gradient of 0.42 GV/m could be realized with an incident laser pulse with peak fluence 20 mJ/cm² and pulse length 100 fs. The high-gradient acceleration of electrons enables a potential miniaturized MeV electron source, which is useful for a variety of applications, such as table-top cancer therapy and university-scale light sources.

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