論文の内容の要旨

Thesis Summary

論文題目　Investigation on Grating-Based Dielectric Laser Accelerator Structures

（回折格子中におけるレーザー駆動誘電体加速器の構造の研究）

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1. Introduction

Particle accelerators have been important tools for scientific research in fields as diverse as high energy physics, materials science, and medicine for the past seven decades. However, due to the electrical breakdown at the metal surface in the presence of strong electric fields, conventional microwave-driven accelerators consisting of metal cavities typically operate with accelerating gradients of a few tens of MV/m, leading to a large size and high cost that severely limit their availability. Dielectric laser accelerators (DLAs) using the strong electric fields available in high power laser pulses in the acceleration have garnered increasing interest in recent years since they can achieve a gradient at the GV/m level by leveraging the high damage thresholds of dielectric materials and in turn, enable smaller and cheaper electron sources. For these reasons, a DLA-based electron source has been proposed to study the damage effect of low radiation doses on the living cell.

In this work, we focus on the development of DLA structures that can facilitate the realization of an electron source. It has been suggested that a double-grating structure could support phase-dependent acceleration and deflection by controlling the relative phase of the drive lasers illuminating each side. In contrast, we proposed a resonant double-grating structure with a single-sided illumination by merging diffraction gratings with resonating Fabry-Perot cavities. In this way, a laser-power efficient way of electron acceleration may be enabled. Besides, we also designed a planar waveguide structure using highly-reflective gratings as mirrors. Compared with the waveguides using photonic crystals, this structure needs only one layer of periodic structures to confine the mode, which may simplify the fabrication and enable easier integration. Additionally, we designed a test station for diffraction gratings, all the components of which have been fabricated.

2. Single-grating structures

A schematic of a generic single-grating structure is shown in Fig. 1(a). The grating diffracts an incident TM-polarized plane wave and generates a series of spatial harmonics, in which one of the evanescent modes is used as the accelerating mode.

In Fig. 1(b), we show the snapshots of the calculated electric field at every half optical cycle, which is comprised of a series of diffraction modes. The maximum longitudinal electric field is located around the corner of the pillar. Above the grating, the fields closer to the grating are modulated more significantly due to the exponentially decaying evanescent fields. For an electron launched $t = 0$, the electric field experienced by the electron is shown by the purple curve. The red dashed line represents the electron beam trajectory and also $E_z = 0$. The average longitudinal electric field experienced by the electron is above zero, so the electron can experience net energy gain over every optical cycle and be accelerated.

Based on the target pulse duration of 30 ps for the laser system at KEK, the maximum incident laser peak field limited by the damage threshold is calculated to be 0.92 GV/m. Figure 1(c) and 1(d) show the corresponding energy gain ΔE and x displacement Δd as a function of the start phase ϕ_0 and initial distance d_0. The white areas represent those electrons crashed into the grating structures, or lost electrons. The characteristics of the single-grating acceleration of non-relativistic electrons are shown clearly, e.g., the accelerating mode is a non-radiative wave and can only accelerate electrons close to the grating surface, the strong deflection force could result in electron loss, and the acceleration and the deflection are $\pi/2$ out of phase.

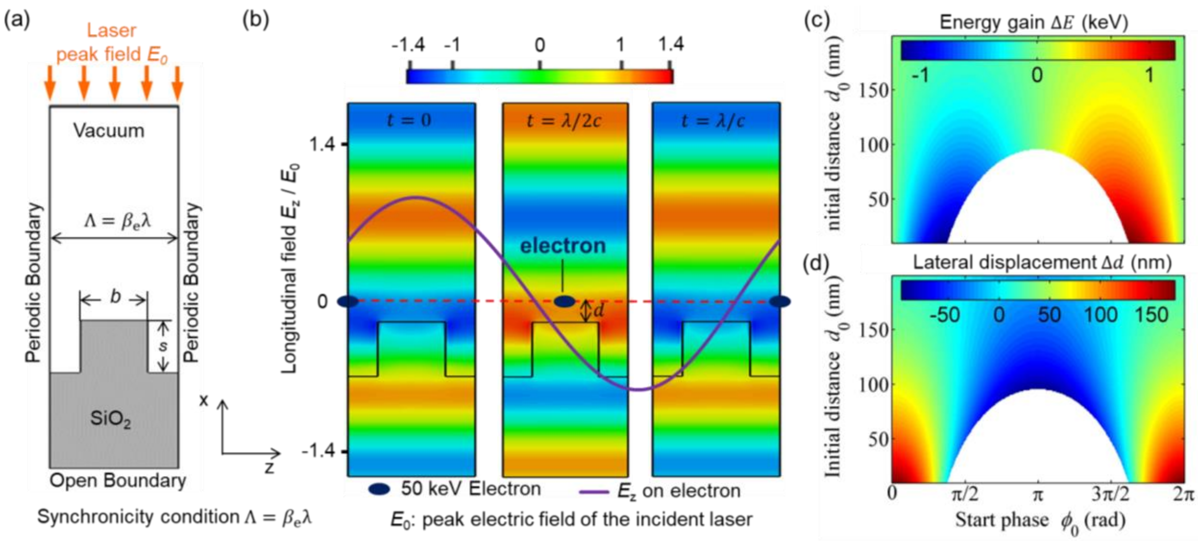

Figure 1: single grating structure and simulation results.

3. Double-grating resonator

By introducing the second grating as shown in Fig. 2(a), the superposition of evanescent modes from the gratings on either side of the channel could form a uniform cosh accelerating mode. For a dual-grating structure illuminated by a single laser, the excitation of the accelerating fields at the lower single grating is dependent on the transmitted zeroth diffraction order from the upper gratings. By making use of the high-reflectivity feature of subwavelength gratings, the accelerating field can be enhanced by resonating with the zeroth diffraction order (plane wave) inside the channel.

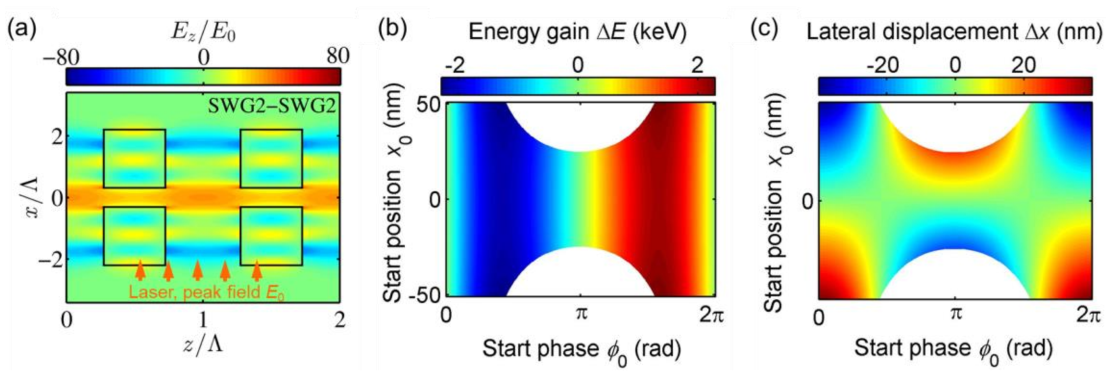

Figure 2: Simulation results of double-grating resonators.

When using SWGs as mirrors in a dual-grating resonator, the channel width d is determined by the round-trip phase condition for the zeroth order $\varphi = 2\psi_{\mathrm{R},0} + 2k_0 d = 2p\pi$, with p being an integer. At the resonant wavelength λ, the superposition of evanescent modes on either side of the channel can form a cosh accelerating mode, for which the Lorentz force is given by

$$F = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} -2A_c r_1/\gamma_e e E_0 \exp\left(-\frac{d}{2\Gamma}\right)\sinh\left(\frac{x}{\Gamma}\right)\cos\left[k_{z,1}z - \omega(t-t_0) - \psi_{\mathrm{R},n}\right] \\ 0 \\ 2A_c r_1/\gamma_e e E_0 \exp\left(-\frac{d}{2\Gamma}\right)\sinh\left(\frac{x}{\Gamma}\right)\cos\left[k_{z,1}z - \omega(t-t_0) - \psi_{\mathrm{R},n}\right] \end{bmatrix}, \quad (1)$$

where $x = 0$ is located at the channel center, $\gamma_\mathrm{e} = (1 - \beta_\mathrm{e}^2)^{-1/2}$ is the Lorentz factor for electrons, $\Gamma = \beta_\mathrm{e}\gamma_\mathrm{e}\lambda/(2\pi)$ is the decay constant of the accelerating mode, $A_\mathrm{c} = 1/\sqrt{1-R}$ is the enhancement factor. This mode has a net accelerating force at the channel center and phase-dependent focusing force directed towards the channel center.

Driven by a Gaussian laser pulse with a beam waist of 5 μm and a grating structure with a total length of 10 μm, Fig. 2(b) and 2(c) show the energy gain and x displacement of 50 keV electrons in the channel of an examples of the double-grating resonator as a function of the start phase ϕ_0 and initial distance x_0. The white areas represent those electrons crashed into the grating structures. The characteristics of cosh accelerating field profile lead to a rather uniform energy gain around channel center, which is desirable for our purpose. There is a phase-dependent focusing or defocusing force towards the channel center. It can be also seen that with such an accelerating mode, operation with a longitudinal focusing leads to a transverse defocusing, which is in agreement with Earnshaw's theorem. To stably accelerate an electron, external focusing component is needed. The maximum energy gain at the channel center is ~ 2 keV.

4. Waveguide with gratings as mirrors

The double-grating resonator uses a standing wave for acceleration. In contrast, hollow-core waveguides using a traveling wave for acceleration can also be a promising candidate for a future DLA. Photonic crystals (PhCs), which are regular arrays or lattices of dielectric elements, are widely used to confine the accelerating wave to the core due to the photonic band gap (PBG) arising from constructive interference of distributed reflections from each periodic layer. Here, we will show that subwavelength gratings can be used as an alternative solution for the reflectors with desirable characteristics including the high reflectivity, smaller volume.

A schematic of the proposed SWG-SWG waveguide structure is shown in Fig. 3(a). It consists of two gratings followed by matching layers on either side of a hollow core. To accelerate electrons traveling in the hollow core, a special symmetric mode described by the following equation should be supported.

$$\begin{aligned} E_z &= E_0 \cos(k_x x)\exp(\mathrm{i}k_z z) \\ E_x &= -\mathrm{i}(k_z/k_x)E_0 \sin(k_x x)\exp(\mathrm{i}k_z z) \\ H_y &= -\mathrm{i}[k_0/(\eta_0 k_x)]E_0 \sin(k_x x)\exp(\mathrm{i}k_z z) \end{aligned} \quad . \tag{2}$$

For speed-of-light electrons, a matching layer should be designed to support such a traveling wave. The thickness of the matching layer is determined by the equation,

$$\tan\left[k_{\mathrm{m},x}(h-d) + \psi_{R,0}/2\right] = -k_{\mathrm{m},x} d/\varepsilon_{\mathrm{m}}, \tag{3}$$

where $k_{\mathrm{m},x}$ and ε_{m} are the x wavenumber and the permittivity of the matching layer. For gratings with TM polarization, the accelerating mode in the waveguide propagate perpendicularly to the ridge direction. In this case, the structure has no variation in the z direction, neither does the fields, so the waveguide can be treated as a 2D structure in the xy plane. In Fig. 3(b) we show an example of the accelerating mode in the waveguide structure, with a core width of 0.6λ. It can be seen that a uniform accelerating mode across the core is provided.

To evaluate the performance of waveguides, we use several examples of gratings as mirrors. The acceleration efficiency is an important parameter that characterizes the laser-to-electron coupling, which is shown in Fig. 3(c). Among those examples, maximum efficiency of 11% can be obtained.

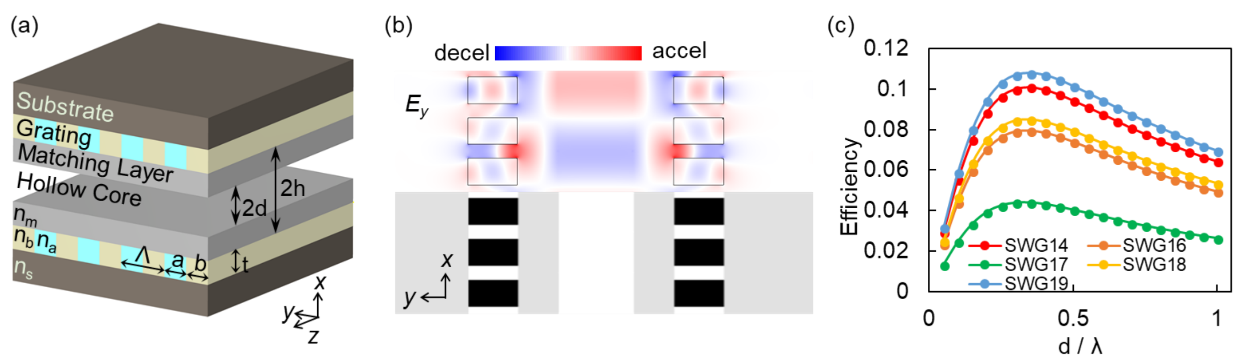

Figure 3: Schematic of the waveguide with gratings and simulation results.

5. A test station in development

A schematic of the experimental setup and the engineering design is shown in Fig. 4(a) and 4(b) respectively. For simplicity, a single-grating structure will be used for debugging. A 50 keV electron beam will be generated with a photocathode. A fiber laser with a central wavelength of 1030 nm will be used to drive the DLA structure. The electron beam trajectory will be controlled with a quadrupole doublet before the grating and a bending magnet after the grating; the latter also serves to measure the electron energy gain.

Dozens of fused-silica single-grating samples have been fabricated with electron-beam lithography and dry-etching technologies. In Fig. 4(c) we show the cross-section SEM images of a fabricated grating. The single-grating structure is located on top of a mesa, which sits above a slab. The mesa structure is required to elevate the grating surface above the slab so that more electrons can pass the slab without beam loss. By incorporating the grating profile as shown in Fig. 4(c) into the CST model, the longitudinal field distribution can be obtained. The corresponding performance of the fabricated sample is very close to the one as shown in Fig. 1(c) and 1(d). Based on the target pulse duration of 30 ps for the laser system at KEK, the maximum energy gain in the experiment is expected to be ~ 1 keV.

Until now, all the components for the experiment as shown in Fig. 4(2) have been fabricated, including the photocathode, high-voltage insulator, vacuum chamber, anodes for the electron gun, doublet and magnetic sector on a base plate. A Yb laser system which provides laser pulses for both the photocathode and DLA structure is almost done. The output beam of the last Yb:YAG thin-disk amplifier has a pulse duration of ~ 50 ps, a pulse energy of 15 mJ, and a repetition rate of 20 Hz. A grating compressor is being developed to realize a shorter pulse duration, which is necessary for high-gradient acceleration. Once the laser is ready, experiments, including the damage test of the dielectric material, electron beam production, dielectric laser acceleration, will be conducted.

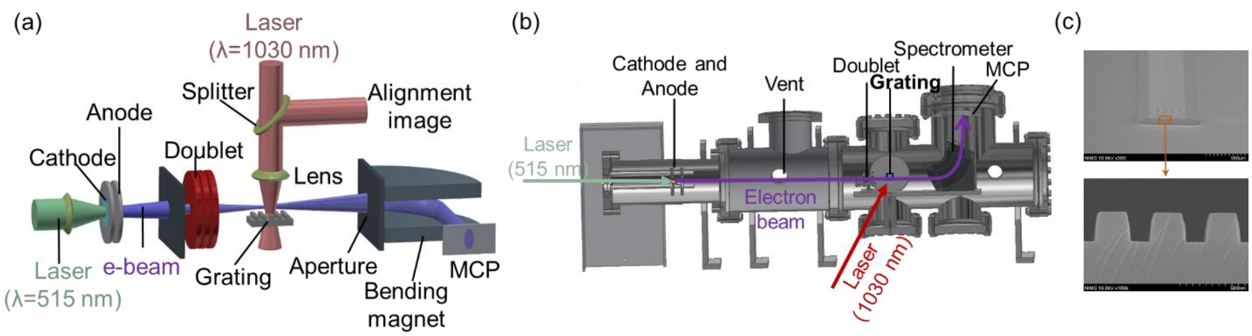

Figure 4: Experimental setup, engineering design, and fabricated grating sample.

6. Conclusions and outlook

We have presented a general method to design a double-grating resonator for subrelativistic electron acceleration. The underlying idea is to merge diffraction gratings with resonating Fabry-Perot cavities. Thus, a laser-power efficient way of electron acceleration may be enabled. We have also described a general procedure to design a planar accelerating waveguide using highly-reflective gratings as mirrors. We found the solution to support an accelerating mode with a given phase velocity by designing a matching layer. Compared with the waveguides using photonic crystals, using a single-layer grating to confine the mode could drastically reduce the transverse size and ensure simpler fabrication. We have also shown the progress in developing a test station for DLA structures. We described our design of the experiment and estimated the sustainable gradient of the fabricated single-grating structure. All the components have been fabricated to date.

In the future, to realize a DLA-based electron source for radiobiology research, there are many bridges to cross. Important steps would probably include the demonstration of a DLA-compatible emitter, optical microbunching, multi-stage acceleration, net acceleration of bunched electrons and beam focusing.