DEVELOPMENT OF A LASER DRIVEN DIELECTRIC ACCELERATOR FOR RADIOBIOLOGY RESEARCH

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Abstract

A laser-driven dielectric accelerator below 1 MeV is under development for applying a sub-micron size electron-beam to radiobiological research. Simulations of the electric field and electron trajectories in the proximity of the dielectric structure (transmission binary phased grating) were performed in order to determine parameters of the acceleration experiment. Serious deflection of electron beam towards the grating surface limited the injection phase as well as the height of the injection point from the grating surface. The energy gain for the 50-keV electron was estimated to be 1 keV in the traveling distance of 15-micron at the optimum condition. Sub-micron pitch gratings for the experiment were fabricated by the electron lithography technique. In addition, a resonator type accelerator structure was studied for producing the acceleration field by a moderately small laser.

INTRODUCTION

Understanding of basic processes of radiobiology and radical chemistry in a living cell is of fundamental importance to radiation therapy [1]. A selective-field irradiation in stead of a broad-field irradiation of individual cells is an important technique to understand a radiation response of the cell. In order to produce a micro-beam for the selective irradiation of a targeted area, a glass capillary collimator is often used, which scrapes off a major part of the intense beam delivered by a big accelerator. However, the capillary wastes the beam current. Another present bottleneck of the radiobiology experiment is a shortage of the machine-time allocation, because a priority object of big machines belonging to hospitals is the radiation treatment for cancer. A tabletop micro-beam machine makes it possible to reduce the waste of the beam as well as to solve a machine-time problem. A dielectric laser accelerator (DLA) and the dielectric wall accelerator seems to be adequate for the tabletop micro-beam machine. The DLA and DWA are suitable for accelerating electrons and ions, respectively. A single ion or 100 electrons of a few-MeV energy in a shot is sufficient for radiobiology experiments [2]. We present recent activities of our DLA research: simulation results, the preparation of the acceleration experiment and preliminary consideration of a resonator-type DLA.

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ACCELERATION WITH A SINGLE GRATING

The electromagnetic (EM) field produced by the irradiation of two phase-matched laser pulse between two parallel binary phase gratings enables to accelerate electrons [3]. Since the dual grating with the two-beam irradiation configuration requires precision assembly and adjustment, it is desirable to design the simpler configuration with single-side irradiation.

A Single Grating with Single-Side Irradiation

In order to determine dimensions of the grating for the acceleration experiment, simulation studies of the EM field and the electron trajectory near the grating were studied. The electron energy was assumed to be 50 keV, which was an output energy of our photocathode electron gun. As shown in Fig. 1, (a) and (b). EM field distributions in one period of the grating were calculated by using CST-STUDIO SUITE®. Since the CST-code took long computation time for solving electron motions in the EM field near the grating, the electron motion was studied by using using the equation of motion and approximate formulas of the EM field, after checking that the analytical solution was agree with the simulation result. We used equations (8) and (9) of Ref. [4] as the EM field of the transverse magnetic (TM) mode and the Lorentz force, respectively.

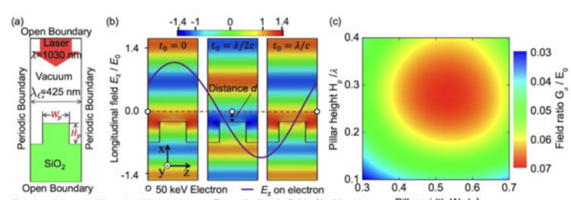

Figure 1: (a) a computational domain. (b) Longitudinal field (Ez) distributions at different phases. Small circles on a z-axis and a sinusoidal curve indicate positions of synchronous electrons of 50 keV and E_z at electrons. (c) A density plot of the acceleration gradient as a function of the pillar height H_p and the pillar width W_p of the grating.

The optimum dimensions of the grating made of silica (SiO_2) were determined by using Fig.1 (c), which was the density plot of the acceleration gradient as functions of the pillar height H_p and the pillar width W_p of the grating. Since the synchronization condition of $\lambda_G = \beta\lambda$ must be satisfied to accelerate electrons continuously, the grating period must

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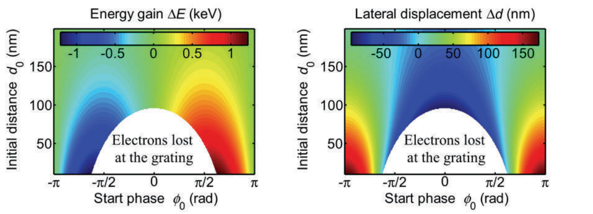

Figure 2: Densityplots of the energy gain and the lateral displacement of the 50-keV electron as a function of the distance from the grating surface (d_0) and the injection phase (ϕ).

be chosen to be 425 nm to accelerate 50-keV electron by the 1030-nm wavelength laser, where λ_G is the grating period, $\beta = v/c$ is the normalized speed of electron v by the speed of light c and λ is the laser wavelength. The maximum acceleration gradient of $0.07E_0$ was obtained at the the pillar hight $H_p = 288$ nm and the pillar width $W_p = 225$ nm, where E_0 is the electric field strength of the input laser.

The acceleration field fall off exponentially perpendicular to the grating surface: the transverse decay length is $\delta = \beta\gamma\lambda/2\pi$, where $\gamma = \left(1-\beta^2\right)^{-1/2}$. Therefore, electron path have to be in the proximity of the grating surface within a distance on the order of the transverse decay length δ to experience acceleration comparable to the maximum accelerating gradient. The non-negligible strength of the transverse component of the Lorentz force strongly bend the electron trajectory and some electrons dive into the grating. Figure 2 shows the energy gain ΔE and the lateral displacement of the 50-keV electron Δd in the traveling distance of 15 μm as a function of the distance from the grating surface d_0 and the injection phase ϕ_0 at the laser intensity of 1.9×10^{12} W/cm^2 ($E_0 = 4.2$ GV/m). The maximum energy gain of above 1 keV might be obtained at the very small window of $\phi_0 = 0.66\pi$ and $d_0 \leq 20$ nm. The most suitable window of ϕ_0 and d_0 for the acceleration experiment seems to be $0.5\pi \lesssim \phi_0 \lesssim 0.7\pi$ and 50 nm $\lesssim d_0 \lesssim 100$ nm.

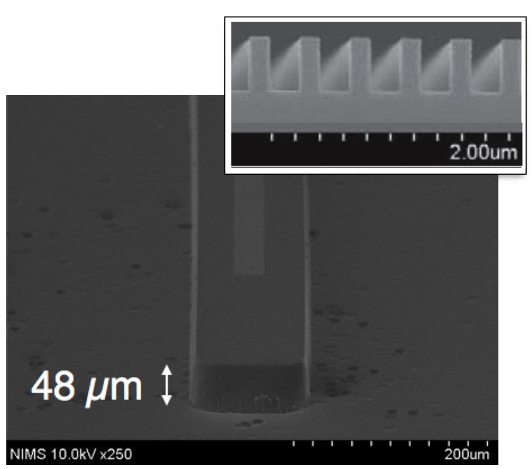

Figure 3: Scanning microscope images of the grating.

Fabrication of the Grating

Since the characteristic length of the grating is shorter then the wavelength used in the i-line stepper (365 nm wavelength), we fabricated gratings by the electron-beam lithography technique at the NIMS Nanofabrication Platform. By adjusting the electron dose and the thickness of metal mask, the gratings with the sub-micron period was fabricated on a 48μm high mesa as shown in Fig. 3. Dimensions of the fabricated grating were $H_P = 272$ nm and W_P (at the top) =153 nm, W_p (at the foot)=218 nm. The small differences from optimum parameters might lead to decrease of the acceleration gradient about 5 %. Since the laser energy of our fiber laser system is limited to 140 nJ/pulse ($\tau_L = 150$ fs) at present, the maximum energy gain is expected to be 1 keV.

DLA WITH RESONATOR STRUCTURE

Presently used DLA structures in experiments waste most of the laser energy, because the laser pulse passes across the accelerator channel only one time. If it is possible to store the laser energy in the accelerator channel, a laser-electron coupling efficiency might be increased. Figure 4 shows that if a quality factor (Q factor) is as high as 100, the field intensity of 10^{13} W/cm^2 would be attained by the irradiation intensity of 5×10^{11} W/cm^2 using 1ps-long to 10ps-long laser pulse.

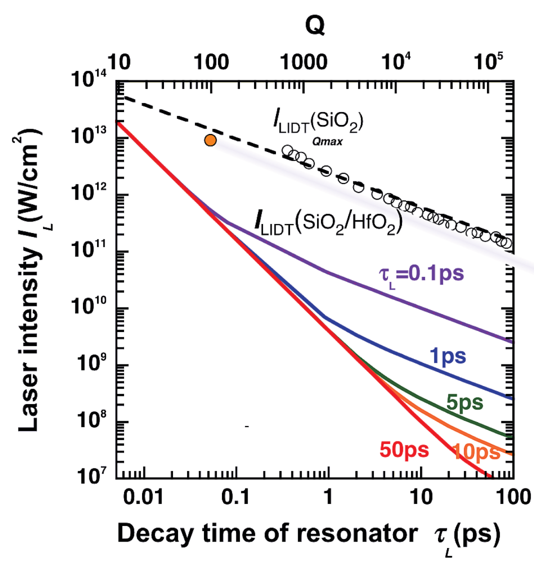

Figure 4: Required laser intensity I_L to produce the field intensity as high as laser induced damage threshold for the silica (open circles and a dashed line) and the SiO_2/HfO_2 multi layer (an orange circle and a gray line).

The optical cavity with the high Q factor is formed by adopting a high Finesse ($\mathcal{F}$) Fabry-Pérot (FP) resonator. The relation between the Q factor and the Finesse is expresser by $Q = (\omega\ell/\pi c)\mathcal{F}$, where ω, ℓ are the angler frequency of the laser and the cavity length, respectively. The high Finesse optical resonator consists of a pair of high reflectance multi-layer mirrors. The reflectivity of eight pairs of SiO_2/HfO_2

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layer is estimated to be $\simeq$ 99.6% and the Finesse is $\mathcal{F} = 390$. LIDTs of SiO_2/HfO_2 multi-layer are 1.4×10^{13} W/cm^2 and 10^{10} W/cm^2 at pulse widths of 500 fs [5] and 3ns [6], respectively. These values are about half of the LIDT of SiO_2 as shown by an orange circle and a gray line in Fig. 4. Since the intensity of 5×10^{11} W/cm^2 is below the LIDT of the silica at the pulse width of 10 ps, a direct coupling of the DLA cavity with an optical fiber will be realized.

Two configurations of the grating is possible: one is that the grating faces the acceleration channel, and the other one is that the grating faces the outside as shown in Fig. 5 (a) and Fig. 5 (b), respectively. It is enough to groove gratings on one of cavity mirrors, because a flat mirror of the other side of the FP resonator forms a mirror image of the grating.

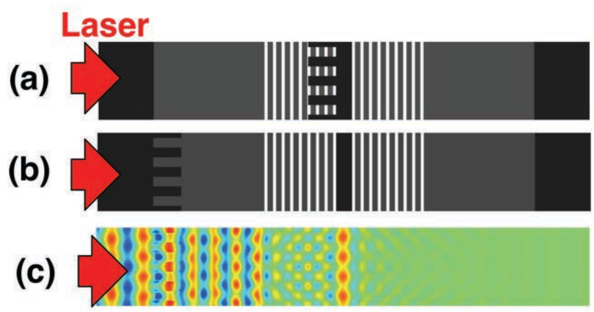

Figure 5: (a) and (b) are possible configurations. The gray level indicates the difference of refractive indexes. (c) is the axial field distribution of case (b).

We are conducting the simulation study on the resonator-type DLA. The configuration of Fig. 5 (a) (the grating faces the accelerator channel) is equivalent to an array of small width cavities, which leads to a small Fresnal number (large diffraction loss) and low Q factor. On the other hand, in case of the configuration Fig. 5 (b) (the grating faces the outside) an enhanced acceleration field is observed as shown in Fig. 5 (c) as a result of the high Q cavity. In order to reproduce the lateral intensity distribution in the cavity through a baseplate of the multilayer mirror, the distance between the grating and the resonator must conform to an integer multiple of the Talbot length, to reproduce the self-imaging in the resonator. Since the Talbot length is expressed as $Z_T = \lambda / \left(1 - \sqrt{1 - \lambda^2/\lambda_G^2}\right)$, the smaller grating period than the laser wavelength is not allowed. Therefore, the configuration of the grating directed outward is applicable to accelerate relativistic electrons.

CONCLUSION

Dimensions of the grating made of fused silica for the acceleration experiment were decided by the simulation. The simulation showed that the acceleration gradient of $0.07E_0$ was attained at the the pillar hight $H_p = 288$ nm and the pillar width $W_p = 225$ nm. Dimensions of the fabricated grating were $H_P = 272$ nm and W_P (at the top)=153 nm, W_p (at the foot)=218 nm. The small differences from optimum parameters might lead to decrease the acceleration gradient about 5 %. Since the laser energy is as small as 140 nJ/pulse ($\tau_L = 150$ fs) at present, the maximum energy gain is expected to be 1 keV at the optimum parameters.

In order to improve the energy transfer efficiency from the laser to electrons, the resonator-type DLA was studied. The FP resonator with high Finesse ($\mathcal{F} \approx 100$) can contain the EM field as high as that of LIDT with moderately low laser intensity of 5×10^{11} W/cm^2. In order to make high Finesse resonator, the grating must face the outside of the FP mirror.

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