

# LASER-DRIVEN DIELECTRIC NANO-BEAM ACCELERATOR FOR RADIATION BIOLOGY RESEARCHES\*

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## Abstract

A dielectric laser accelerator (DLA) consists of single or a pair of binary blazed transmission grating. In case of normal incidence, a normalized grating constant  $L_G/\lambda_0$  should be equal to a normalized velocity  $\beta = v/c$  to synchronize with the electron and an acceleration field;  $L_g/\lambda_0 = N\beta$ , where  $N$  is the harmonic order of the spatial distribution of the acceleration field. We performed simulation at various conditions with the aid of CST-code as well as meep-code before designing a practical system. Both results of acceleration gradients calculated by the field simulation and PIC simulation had the same values as  $E_x/E_0 = 0.021$  and  $E_x/E_0 = 0.147$  for the grating constants of  $L_g = 850 \text{ nm}$  and  $L_g = 425 \text{ nm}$ , which correspond with acceleration by lower order spatial mode of  $N = 2$  and  $N = 1$ , respectively. Besides analytical works, we fabricated gratings and developed an Yb-doped fiber laser for the acceleration experiment. Gratings of two different materials, a glass silica and crystal silica, were fabricated by the electron beam lithography technique.

## INTRODUCTION

In order to estimate the health risk associated with a low radiation dose, basic radiobiological processes must be clarified by irradiating a cell with a well-defined microbeam of ionization radiation at a precisely defined location under an optical microscope. The use of microbeams of X-rays, electrons, and light and heavy ions for radiobiological applications and microfabrications has substantially increased since the early 1990s. A simple and low-cost device called a tapered capillary made of glass can deliver submicron ion beams. The majority of ion accelerators used at microbeam facilities are Van de Graaf accelerators or cyclotrons. X-ray and electron microbeams have also been developed in order to provide useful tools for quantitative analysis in radiation biology research that is complimentary to the ion microbeam. Electron microbeams are easily obtained by using electron microscopes. However, the low-energy electron beam has a troublesome scattering problem.

The dimensions of beam sources such as MeV-class ion accelerators, synchrotrons for hard X-ray radiation and MeV-class electron microscopes are extremely large such that only a limited number of facilities can install them. If

the size of an accelerators is reduced to be an order of magnitude smaller than that of present accelerators, many radiobiological studies will be performed at small laboratories. Since the DLA has the potential to realize an on-chip accelerator, the research and development of DLAs have been conducted at various institutes.

A combination of a high-frequency electric field and a material with a high dielectric breakdown voltage are indispensable to overcome the limitation of the acceleration gradient. An intense laser pulse and the periodic structure of a dielectric such as silica is capable of increasing the acceleration gradient by an order of magnitude compared to that of a conventional radio-frequency (rf) accelerator. A phase-modulation-type laser accelerator made of a dielectric grating was proposed by Plettner [2], which is much simpler than the two-dimensional [3] and three-dimensional waveguide structures [4]. A typical shapes of a single grating DLA is shown in Fig. 1.

We are studying a structure of the laser field in a proximity of the transmission gratings with the help of numerical simulation codes, meep and CST for designing gratings for the acceleration experiments. In order to avoid the difficulty of an ultra-precision assembling of a dual grating structure, we concentrate on a single grating structure for the present.

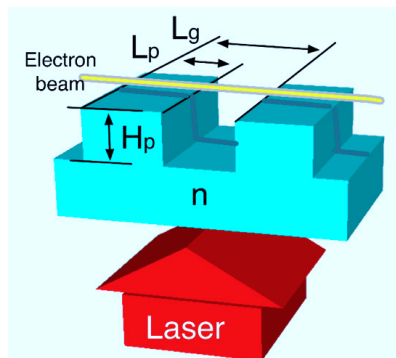


Figure 1: Schematic drawing of DLA.

## REQUIRED SPECIFICATIONS

The DLA system for the radiobiology research is schematically drawn as Fig.2 The specifications of the beam for the radiobiological research are listed below [1].

1. A beam size is as small as a resolving power of an optical microscope of submicron.

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- Required beam energy and bunch charge are in the range from 0.5 MeV to 1 MeV and from 0.01 fC to 1 fC, respectively. The lower limit of the energy range mentioned above is derived from the condition to limit a beam expansion to less than 1  $\mu\text{m}$  when passing through a biological cell. The upper limit is defined by the regulation of the radiation protection.
- A size of the accelerator is as small as to install under the optical microscope.
- A laser and optical system should be stable and compact.

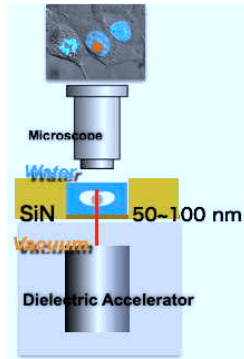


Figure 2: The conceptual drawing of the DLA system for the radiobiology research.

## ACCELERATION GRADIENT

The analytically derived optimal dimensions for the grating constant ( $L_g$ ) and pillar height ( $H_p$ ) are  $L_g/\lambda_0 = N\beta$  and  $H_p/\lambda_0 = 1/(2(n-1))$ , respectively, where  $\beta = v/c$ ,  $\lambda_0$ ,  $N$  and  $n$  are the normalized speed of electron, the laser wavelength in vacuum, the harmonic order of the spatial distribution of the electric field and the refractive index of the grating, respectively. The distance from the grating surface is limited only in the proximity of the grating surface ( $y \lesssim \lambda/4$ ), A numerical analysis is required in addition to the analytical estimation for finding optimum dimensions.

We investigated the optimal dimensions of transmission gratings for the incident beam energy of 50 keV, which was the output energy of our electron gun. The laser wavelengths were 1030 nm (Yb-fiber laser) and 800 nm (Ti:sapphire laser). The grating material was the silica ( $\text{SiO}_2$ ). A normalized average-acceleration gradient at 100  $\mu\text{m}$  apart from the grating was estimated by the field simulation and particle-in-cell (PIC) simulation. At the grating constant of  $L_g = 1275$  nm, which corresponds to accelerate 50keV electron with  $N = 3$ , the acceleration gradient reached its maximum value of  $E_x/E_0 = 0.03$  at a filling factor of the grating of  $L_p/L_g = 0.5$  and pillar height of  $H_p/\lambda_0 = 1$ . Small variations of etching conditions tended to introduce errors in the pillar height  $\Delta H_p$  and a slope of a side wall of the pillar  $\Delta\theta$  (the deviation angle from the vertical). The tolerable error in pillar height must be

$\Delta H_p/H_p \leq 10\%$  to keep  $\Delta E_x/E_x < 5\%$ , which is similar to the simulation for the relativistic electron energy [5]. The effect of a finite slope angle of a pillar-sidewall on the acceleration is under investigated for the single grating configuration.

Both the results of acceleration gradients calculated by the field simulation and PIC simulation had the same values as  $E_x/E_0 = 0.021$  and  $E_x/E_0 = 0.147$  for the grating constants of  $L_g = 850$  nm and  $L_g = 425$  nm, which correspond with acceleration by lower order spatial mode of  $N = 2$  and  $N = 1$ , respectively.

## FABRICATION OF TRANSMISSION GRATINGS

We fabricated transmission gratings (on silica ( $\text{SiO}_2$ ) plates) by an electron beam lithography technique. Dimensions of the fabricated grating were  $L_G = 560$  nm,  $L_P = 280$  nm and  $H_P = 440$  nm. The etching rate of  $y_d = 0.911t - 29.9$  was measured for a crystal quartz at NIMS-Nmiki-site in advance, where  $y_d$  and  $t$  were the etched depth (nm) and etching time (s), respectively. Two different material structures of silica, the crystal quartz and a glass silica, were processed with same etching conditions. The grating constant and the pillar width measured by using the variable pressure scanning electron microscope (VP-SEM) were  $L_G = 550$  nm and  $L_P = 238$  nm, respectively. The groove depth measured by an atomic force microscope (AFM) were 421 nm and 583 nm for the crystal quartz and the silica glass, respectively. The AFM images show many tall humps at the bottom of the groove of the transmission grating made of the crystal silica as seen in Fig. 3. The typical diameter and height of the hump were in the range of 100 nm - 300 nm and 140 nm - 400 nm, respectively. On the other hand, the sparse and smaller humps were seen in the groove of glass silica transmission grating. The size was as small as 20 nm - 50 nm. It is difficult to know the exact inclination of the side wall of the pillar owing to the shape of the cantilever of the AFM.

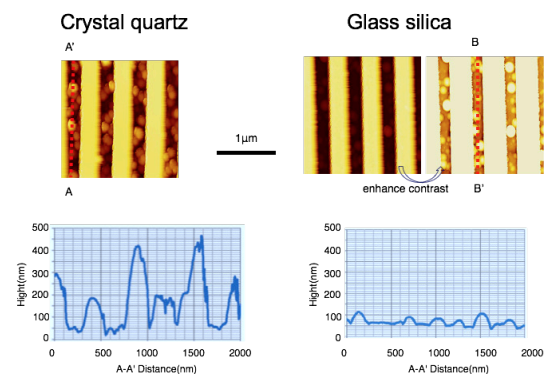


Figure 3: AFM images and cross-sectional shapes, along lines of A-A' and B-B', of bottom of grooves of gratings made of crystal quartz and glass silica.

Recently we changed fabrication facility to "NIMS Nanofabrication Platform" because of the machine trouble in previous site. Dimensions of the transmission grating was designed to accelerate 50keV electrons by the fundamental spatial mode of acceleration field of the Yb-laser. The SEM image of a cut surface of the transmission grating fabricated at new platform showed the grating of trapezoidal-pillar. Dimensions were  $L_G = 424.6 \text{ nm}$ ,  $L_p = 174.6 \text{ nm}$ ,  $H_p = 349.3 \text{ nm}$ , and the slope angle of the side-wall of the pillar was  $78.8^\circ$  (Fig.4). We are performing the simulation for the trapezoidal-pillar grating in order to evaluate the trapezoid effect on the acceleration.

and  $L_g = 425 \text{ nm}$ , which correspond with acceleration by lower order spatial mode of  $N = 2$  and  $N = 1$ , respectively. While the transverse deviation of electron was negligibly small, the electron injected in the proper phase was accelerated accompanied by a small longitudinal velocity modulation. In case of the continuously injected electrons, some of them were accelerated and some of them decelerated. This led to the modulation of electron energy distribution.

The large humps of several hundred nm size were observed in grooves of the transmission grating made of the crystal silica. The glass silica transmission grating had smoother grooves. The glass silica was more suitable for making the high aspect ratio grating.

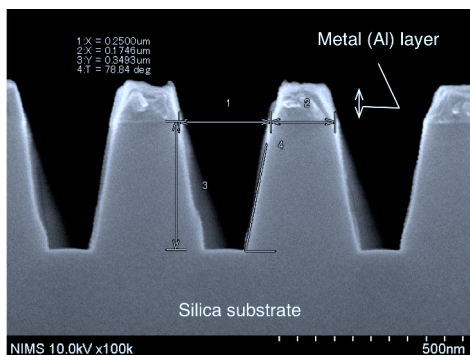


Figure 4: The SEM image of the transmission grating cross-section before the removal of metal coating.

### SUMMARY

The field structure and particle motions of the laser driven dielectric accelerator were studied by using the simulation code, CST. Acceleration gradients derived by the field simulation and PIC simulation were  $E_x/E_0 = 0.021$  and  $E_x/E_0 = 0.147$  for the grating constants of  $L_g = 850 \text{ nm}$

### ACKNOWLEDGEMENT

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