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DEVELOPMENT ON ON-CHIP RADIATION SOURCE USING DIELECTRIC LASER ACCELERATOR*

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Abstract

We present a new and simple configuration of Dielectric Laser Accelerator (DLA), which can accelerate particles at widely arbitrary $c\beta$ and can efficiently generate higher acceleration gradient using highly compressed laser pulse. We also report on the progress in first experiments for its demonstration and future application for radiation biology.

MOTIVATION

The laser damage threshold of dielectric material is orders of magnitude stronger than that of metal against microwave. DLA is the micro-fabricated accelerator made of such dielectric structures which diffract the laser pulse and produce high accelerating gradient (i.e., > 200 MV/m). Also, using the infrared lasers, the beam radius of micro-meter and bunching in sub-femto-second are expected. In addition, the mass productivity of the DLA based on the consumer-grade laser and the photolithography has advantage compared to the conventional RF accelerator using high power klystrons. Such features suggest that development of on-chip DLA is suitable for radiation biology researches: to hit and damage the target elements of the cells can strongly assist the researches where the accurate and big statistical data is needed, i.e., investigation on bystander effects. Table 1 shows the consequent objective parameters. The electron beam (or X-ray) with small radius and adequate intensity required for this goal can be obtained using sub-micron beams from the small accelerating structure at high repetition rate (such as 50 kHz).

Table 1: Requirements for the radiation biology research

Beam size	~ 1	μm
Bunch charge	~ 0.01 to 0.1	fC
Beam energy	< 1	MeV
Bunch length	< 1	fs

OBLIQUE INCIDENCE DLA

Future development of transmission type DLA

First demonstrations of DLA for electron at speed of light and at non-relativistic speed are reported respectively last year [1][2]. These DLA are categorized in transmission type where the laser pulses are induced perpendicularly against the grating, and have advantage in availability in bulk production of the dielectric structure, and facility to get higher current among DLA. Following researches on these DLA would be focused on:

- Increasing the total energy gain
- Overcoming the difficulties to accelerate particles at low β

The former is now restricted by the dilemma: pulse compression to get higher acceleration gradient makes acceleration gap shorter, resulting in lower energy gain. One suggested solution is to separate the one laser pulse into pieces in terms of space and time so that particles are accelerated in high energy density and continuously, while the high demands on precise optical alignment might be one drawback.

The difficulties in the latter problem lie in the use of higher order harmonic field. Not only generation of such harmonic seems difficult, but only discrete β which can be accelerated at non-relativistic speed.

Concept and Feature of Oblique Incidence DLA

Figure 1 a) shows the schematic image of our concept of DLA, which we call Oblique Incidence DLA (OI-DLA). The difference of setup from other transmission type DLA's are the introduction of the prism, and the glancing angle θ smaller than $\pi/2$. (Here, laser is s-polarized.) With this configuration we can avoid the difficulties mentioned above as follows:

- Highly compressed laser pulses can be induced since beam radius is the dominant factor to decide the acceleration gap, leading to the higher accelerating gradient with relatively compact laser source.
- The tilted wave-front in a prism shape refractive medium leads the suitable delay to match the phase advance of the electron beam.

Principle on Phase Matching of OI-DLA

Figure 1 b) is schematic view of matching the speed of particle and accelerating field.

Depth of Grating The depth of the grating H is chosen to make the difference of optical path length of a half laser wavelength λ:

$$(n-1)\frac{H}{\lambda} = \frac{1}{2} \quad (1)$$

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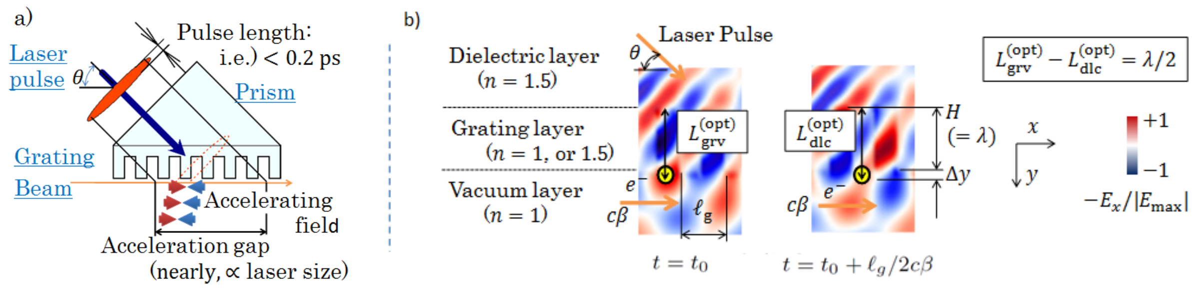

Figure 1: Schematic view of OI-DLA: a), and the principle of matching speed of electron and laser phase :b)

Here n is the refractive index of grating. One might feel strange that the we are neglecting the incidence angle θ. But, since the grating structure is designed to be smaller than laser wavelength, the propagation explained by Huygens-Fresnel principle shows that the propagation is (nearly) directed into the normal of grating surface, transforming wave-front parallel to the beam axis. Assuming the refractive index n is 1.5, depth of the groove $H = \lambda$ gives difference of optical path length of $\lambda/2 = L^{(opt)}_{grv} - L^{(opt)}_{dlc}$ on the beam axis between the light which propagates through the groove and dielectric block (see Figure 1 b)), which let certain flux of particles feel the accelerating field continuously. (Those conditions nearly corresponds to the SiO_2 grating and prism, whose index is 1.46.).

Matching Speed of Particle and Laser Phase At $t = t_0$ in figure 1 b), we assume that the electron at speed of β is moving right direction and in the accelerating field. In general, the phase speed of light projected in the beam direction ($v_p = c\cos\theta/n$) is faster than that of electrons when $\beta < 1$. Here, the grooves and the blocks appearing repeatedly when the distance the particles feel the decelerating field to let the particles accelerated continuously. This condition corresponds to the timing when distance between the particles and the accelerating phase become a half wavelength projected into the beam axis, which gives equation of ℓ_g:

$$(v_p - c\beta)\frac{\ell_g}{2c\beta} = \frac{\lambda}{2n\cos\theta}. \quad (2)$$

Solving this on β, we obtain

$$\beta = \frac{1}{n \quad \cos\theta + \lambda/\ell_g}. \quad (3)$$

Eq. (3) means particles at arbitrary speed of $c\beta$ would be on accelerating phase continuously, only adjusting the incident angle θ, as long as $0 < \theta \leq \pi/2$. Such parameters are feasible: For instance, particles at $\beta = 0.4$ can be accelerated using a SiO_2 grating and a prism, and Yb-laser, where $n = 1.46$ and $\lambda = 1.035$ μm, and $\ell_g = 0.7$ μm and $\theta \sim \pi/2$ satisfies eq. (3)..

Simulation on Accelerating Filed

We have employed FDTD simulation to obtain the accelerating field. We chose SiO_2 as the material of the grating and the prism because it is compatible with the lower cost and higher enough laser damage threshold [3]. Also, we chose Yb ultra-short laser-pulse system, whose wavelength $\lambda = 1.035$ μm, because of its higher energy converting efficiency and wide band frequency. In Figure 2 shows the time dependence of electric field in beam direction E_x along $\Delta y = \lambda/3$, $4\lambda/3$ slice from the grating surface (see Figre 1 b)). Gaussian Laser pulse whose duration is longer enough against the λ/c the refractive index of $n = 1.46$ (SiO_2) in the grating and prism are assumed. The dimensions are normalized by wavelength as $H/\lambda = 1.125/1.035$, $\ell_g/\lambda = 0.7/1.035$. The incident angle θ is $\pi/4$. In the figure, the line 1 is parallel to the trajectory of particles at constant speed of $\beta = 0.398$, which is derived from eq. (3). Simulation results agree well with the design speed of the accelerating (traveling-wave-like) field, while electrons at that speed are expected to slip from the accelerating phase within < 10 pitches of the grating structure, assuming the acceleration gradient is 200 MV/m. The field vary gradually and decay (like evanescent wave) along y axis. (Here we do not consider non-linear effects.)

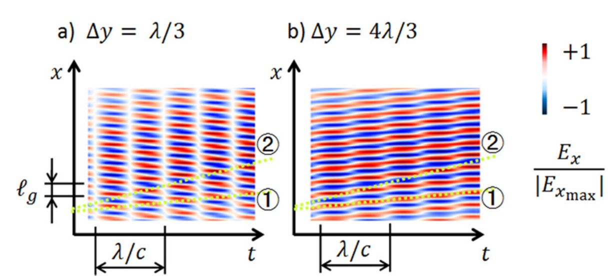

Figure 2: Propagation of E_x on x-t plane at Δy (The line 1 and 2 correspond to $\beta = 0.4$ and 1, respectively.)

EXPERIMENTAL SETUP FOR DEMONSTATION OF OI-DLA

We are preparing for demonstration of OI-DLA. The schematic view of the experiment is shown in Figure 3. In the experiment, the electron beam with the energy of 50 keV (β~0.412) and current of 2 mA generated from the DC electro gun is focused and collimated into beam radius of < 0.1 mm at the accelerating pint. The ultra-short laser pulses with the pulse energy of ~10 μJ and pulse length of ~0.2 ps is focused into ~0.1 mm × 1 mm and induced to the prism. Here, to get the mean current of ~ pA for accelerated electrons, the repetition rate of laser pulse is chosen as high as 50 kHz. Subsequently, the

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energy spread of the accelerated beam is projected into space using magnet spectrometer. According to the model simulation using traveling wave tube scaled into the size and accelerating gradient of 200 MV/m, the energy gain of the beam is roughly predicted to be ~1 keV, which is low to achieve the requirement, since structures to deal the increasing speed of particles are yet to be designed.

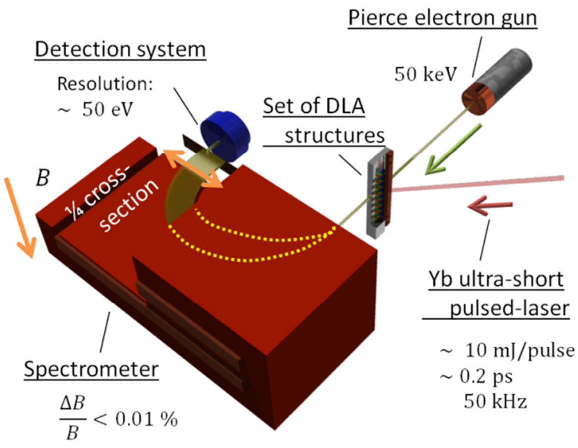

Figure 3: Schematic view of experimental setup.

PREPARATION AND PRELIMINALY EXPERIMENTS

SiO_2 *Grating*

We are fabricating rating structure on the SiO_2 wafer with so called "lithography, "which is often used for semiconductor processing. Figure 4 a-1) is one of such wafers, and we have determined the conditions for larger two pitches. Figure 4 a-2) is one of the SEM images of them.

Pierce Electron Gun

We chose the thermal Ir cathode to obtain beam current of 2 mA, which let the designed beam current of accelerated electrons reach ~ 1 pA. To focus such high current along the DLA area, we designed Pierce electron gun and solenoid magnet.

Yb ultra-short laser-pulse system

Yb ultra-short laser-pulse system has been developed, which is now operating at pulse energy 10 μJ , repetition rate of 1 MHz, and pulse duration of 1 ps (Figure 4 b)). We are adding the CPA to increase the pulse energy up to ~ 10 μJ at 50 kHz , and the compression chamber to get pulse duration of 0.2 ps.

Spectrometer and Detector

Designing of the magnetic spectrometer and the detector is finished. The resolution is designed to be ~ 50 eV so that we can detect the energy gain of 0.1 % against the initial beam energy. The design error of the magnetic field is $B/\Delta B < 0.01$ %.

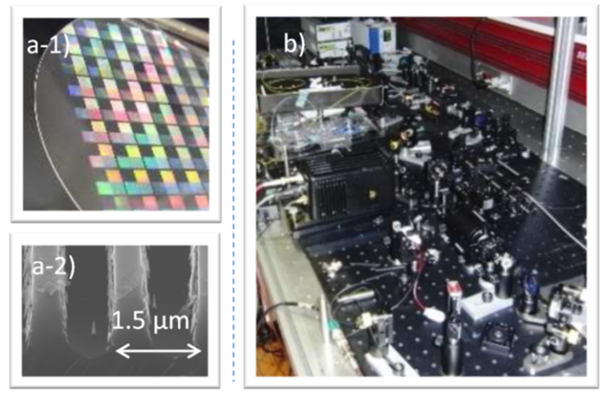

Figure 4: a-1) Test piece of grating on SiO_2 wafer (11 × 11, 4 different pitches in each coordinate), a-2) SEM image of SiO_2 grating, and b) Yb ultra-short laser-pulse system

CONCLUSION

We are developing an on-chip micro-beam accelerator designed for radiation biology researches. We proposed the new configuration of transmission type DLA with oblique incidence of laser pulses and a prism, which allows it possible to accelerate particles at widely arbitrary β, and use of highly compresses laser pulses to achieve higher acceleration gradient using more compact laser system. Simulation results of traveling-wave-like accelerating fields agree with those theoretically expected. Parameters of grating and laser for the required electron beam for the application in the radiation biology researches are feasible. We are now preparing for demonstrating OI-DLA for electrons at $\beta = 0.4$ (50 keV) using Yb ultra-short laser-pulse system. On the other hand, phase slip occurs within < 10 pitches for electrons, which we are going to design the buncher-like structures to avoid. Processing conditions of SiO_2 grating is determined in several accelerating conditions. The designing of the experimental setup including the DC electron gun, the spectrometer, and the detection system are finishing.

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