DESIGNING OF PHOTONIC CRYSTAL ACCELERATOR FOR RADIATION BIOLOGY*

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Abstract

In order to investigate fundamental biological processes in a cell, a DNA is precisely hit by an electron bunch with an in situ observation of a radiation interaction using a microscope. A photonic crystal accelerator made of a dielectric material pumped by a fiber laser is suitable for such objectives. Parameters of the accelerator structure as well as the required electron injection speed are studied. In the case where the grating period is half of the laser wavelength and the laser illumination intensity is 10^{13} W/cm^2, the electron is accelerated from 79 keV to 1 MeV in a 3.3-mm-long accelerator. The required laser power for one side is 10 GW/pulse. If the pumping laser pulse is divided into 15 pulses, the laser energy per pulse is 7.3 mJ and the pulse width of the laser pulse is 1.1 ps. A fiber laser with many branches seems to be suitable for pumping the accelerator.

INTRODUCTION

In order to estimate the health risk associated with a low radiation dose, basic radiobiological processes must be clarified by hitting DNA by using a spatially and temporally defined particle beam or X-ray. The suitable beam size is as small as the resolving power of an optical microscope with a resolution of a few hundred nanometers. The required beam energy and bunch charge, which depend on the thickness of the specimen, are in the range of 100keV to 1MeV and 0.1fC to 1fC, respectively. Moreover, it is convenient to use an accelerator that is small enough to be handled under the optical microscope. Photonic crystal accelerators (PCAs) are capable of delivering nanometer beams of subfemtosecond pulses because the characteristic length and frequency of accelerators are on the order of those of laser light.

Since a phase-modulation-mask-ype laser-driven dielectric accelerator (PLDA) has a simpler structure [1] than other types of PCAs[2], we studied the PLDA. Because we focused on a lower-energy accelerator compared to the accelerator considered in other published works, the optimum dimensions of the PLDA were determined. The structure and dimensions of the PLDA as well as the required laser power, are discussed in this paper.

STRUCTURES

Preliminary Analysis

The structure of the PLDA is expressed in terms of the grating period, L_G, width of the grating pillar, L_p, height of the pillar, H_p, and the distance between opposite pillars, D (see Fig. 1). The length of the pillar, i.e., the width of the accelerator channel, W, is assumed to be much larger than L_G for simplicity. The propagation of the laser pulse in a direction orthogonal to the electron beam is a marked feature of the PLDA. This feature facilitates the acceleration of electrons from non-relativistic to relativistic energies. Laser pulses, which are linearly polarized parallel to the axis of the electron beam, pass through the pillar and vacuum depending on their longitudinal position of the accelerator. An electric field along the beam axis behaves like a standing wave when the optical path difference between two paths through the pillar and vacuum is tuned to the half-period of the laser light. The relation between the speed of the injected electron, v_0, and L_G is obtained as follows by approximating the axial electric field by a sinewave, where λ is the wavelength of the laser light.

$$v_0/c = L_G/\lambda. \tag{1}$$

The normalized pillar height of $H_p/\lambda \approx 1/\left(2\left(n-1\right)\right)$ is determined by considering a path difference of π, where n is the refractive index of the pillar material. The distance between opposite pillars is assumed to be $D/\lambda < 1/4$ from the range of an evanescent wave. Precise values of these parameters must be fixed by using a computer simulation code because the field distribution might be deformed by its higher-order modes and reflected light. L_G must be grad-

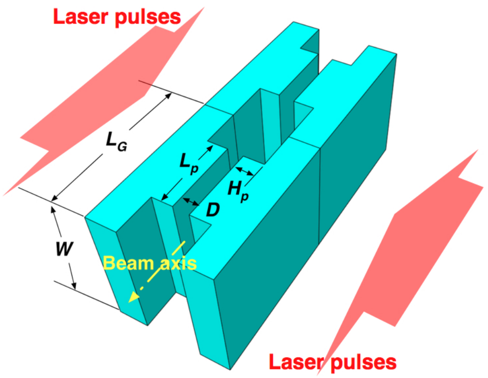

Figure 1: Schematic drawing of two periods of an accelerator unit.

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ually changed as shown in Fig. 2(a). The evolution of the energy gain along the beam axis is shown in Fig. 2(b). For example, at the grating period of $L_G/\lambda = 0.5$, the corresponding electron injection energy is 79 keV. In this study, the ratio of the width of the pillar to the vacuum region, $L_p/(L_G - L_p)$, is set to be 1. The normalized pillar height is $H_p/\lambda \approx 1.1$ at the refractive index of $n = 1.44$. The accelerator length required to obtain an acceleration gain of 1 MeV is approximately 2,200 times the laser wavelength, as shown by the dotted lines in Fig. 2(b).

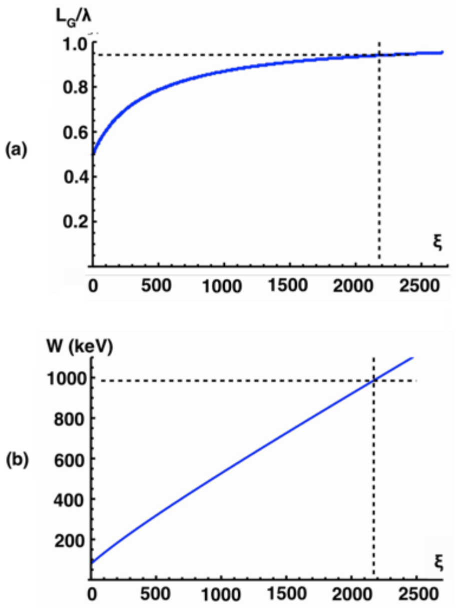

Figure 2: (a) Variation of the period of the grating, L_G. (b) The energy gain W. $\xi = x/\lambda$ is the normalized coordinate parallel the accelerator axis. A field strength of 8.7 GV/m was assumed to calculate the energy gain. Dotted lines correspond to a 1 MeV energy gain.

Simulation

The electromagnetic field analysis computer code based on the boundary element method, CST Microwave Studio^{TM}, is used for examining the parameters of the accelerator mentioned in the previous subsection. Since the phase velocity of the laser light in the pillar is lower than that in the vacuum, the pillar tends to focus the laser light as shown in Fig. 3. The focusing effect of the pillar deviates the field distribution from a simple harmonic distribution. A simple harmonic field distribution might be produced by changing the ratio of H_p to L_G.

LASER PARAMETERS

The the laser light intensity at the surface of the dielectric material must be kept below the damage threshold value I_{th} [2]. The required laser pulse energy for one side, E_L, is determined by multiplying the illumination area A and the pulse width τ_L: $E_L(1) = I_{th} A \tau_L = I_{th} L_A^2 W / \langle v \rangle$, where L_A, W, and $\langle v \rangle$ are the accelerator length, accelerator channel width, and average velocity of the electron, respectively. In order to decrease the laser pulse energy, the laser illumination area and time around the electron bunch must be limited by synchronizing the laser pulse with the electron bunch. If the accelerator is illuminated by sequential N pulses, the laser pulse energy is decreased to

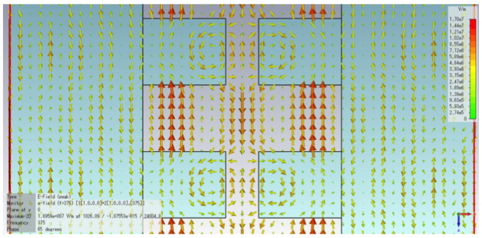

Figure 3: Vector plot of the electric field in the dielectric material and vacuum for $L_G = \lambda, L_p = L_G/2, H_p = 0.441\lambda$, and $D = \lambda/4$.

$$E_L(2) = I_{th} L_A^2 W / (\langle v \rangle N). \tag{2}$$

The pulse width is expressed as $L_A/\langle v \rangle/N$. For producing such an illumination scheme, Plettner [1] proposed that the short laser pulse be divided into many segments by mirrors and that each pulse be introduced into the accelerator through a properly tuned optical delay. However, the use of many optical mounts is inconvenient for our purpose. A fiber laser might increase the freedom of the configuration, as shown in Fig. 4.

Assuming that the accelerator width was greater than the laser wavelength by a factor of a few tens and that the laser wavelength was 1.5 μm (Er-fiber laser), rough estimates of the laser parameters were obtained for one side; the estimate are shown in Table 1. The damage threshold intensity used in the estimation was $I_{th} \approx 10^{13}$ W/cm^2 $(E_{th} \approx 8.7 \times 10^7$ V/cm$)$ for SiO$_2$ at a pulse width in the range 100 fs to 1ps [3] .

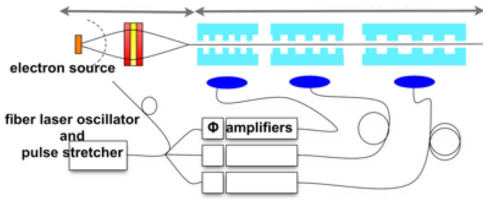

Figure 4: Sketch of a fiber-laser-pumped dielectric accelerator. Φ is the phase controller.

DISCUSSION AND SUMMARY

The phase-modulation-mask-ype laser-driven dielectric accelerator is simpler than other types of phtonic crystal

Table 1: Laser parameter values required for obtaining 1 MeV electrons

Period of the structure	0.5 to 1λ (see Fig. 2(a))
Electron injection energy	79 keV
Width	30 μm
Length	3.3 mm
Area	1×10^{-3} cm^2
Acceleration time	11 ps
Laser power	10 GW
Pulse energy of one side	110 mJ
Pulse width	11 ps
Number of pumping pulses	15
Energy of each pulse	7.3 mJ/fiber
Pulse width	1.1 ps

accelerators. Moreover, it is easy to use the accelerator to accelerate initially slow electrons. Parameters of the accelerator structure as well as the condition for the injection speed of electron are studied. In the case when the grating period is $L_G/\lambda = 0.5$ and the laser intensity used for producing the acceleration field is 10^{13} $\mathrm{W/cm^2}$, the electron is accelerated from 79 keV to 1 MeV in a 3.3-mm-long accelerator. The precise designing must be performed with the help of a computer simulation by considering the effect of a transverse component of the electric field. The required laser power for one side is 10 GW/pulse. If the pumping laser pulse is divided into 15 pulses, the required laser energy per pulse is 7.3 mJ and the pulse width of the laser is 1.1 ps.

In order to decrease the initial electron energy, the grating period must be smaller than half of the laser wavelength. We are studying the minimum grating period required for ensuring a standing-wave-like acceleration field.

The latest ultrashort pulse fiber laser delivers a 1-ps pulse with a peak power of 1 GW at a repetition rate of 50 kHz [4]. Although these parameters are about 1/10 of the required values, the rapid progress of laser technology is expected to ten times increase of the laser power in the near future. If the laser power is limited to around the present value of 1 GW, the accelerator length must be increased to 33 mm to obtain 1 MeV electrons.

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