DESIGNING OF A PHASE-MASK-TYPE LASER DRIVEN DIELECTRIC ACCELERATOR FOR RADIOBIOLOGY*

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Abstract

In order to develop a useful tool for the basic investigation of the radiobiology, the laser driven dielectric accelerator is studied. From the viewpoint of the fabrication, our effort is focused on the phase-modulation-mask-type laser-driven dielectric accelerator (PLDA). The required beam energy and bunch charge, which depend on the thickness of the specimen, are in the range of 100 keV to 1 MeV and 0.1 fC to 1 fC, respectively. The simulation results by using the FDTD simulation code, Meep, showed that the minimum grating period, was $L_G/\lambda = 0.5$ for the original type of PLDA provided that the accelerator structure was made of silica. The initial electron speed was $v = 0.5c$ (79 keV) to match the minimum grating period of PLDA. The optimistic value of the required total laser energy is 4 mJ for obtaining 1 MeV electron bunch. The acceleration field was also produced by the inside-out accelerator structure. However, L_G/λ was limited to longer than 0.6 in the preliminary simulation result.

INTRODUCTION

Radiobiologists desire to understand basic radiobiological processes around DNAs in living cells in order to estimate the health risk associated with a low radiation dose. Compact devices which deliver the spatially and temporally defined particle bunches or X-ray pulses serve to accomplish the purpose. The suitable beam size is as small as the resolving power of an optical microscope with a spatial 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 100 keV to 1 MeV and 0.1 fC to 1 fC, respectively. Moreover, it is required that one can aim at the target specimen using 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.

A phase-modulation-mask-type laser-driven dielectric accelerator (PLDA) has a simpler structure [1] than other types of PCAs[2,3]. Since the required output energy of the accelerator for the radiobiology is in the non-relativistic or weakly relativistic region the parameters of the PLDA is different from previously published one [1]. The structure and dimensions of the PLDA as well as the required laser power are discussed in this paper.

DIMENSIONS OF THE ACCELERATOR

The structure of the original type of PLDA is expressed in terms of the grating period L_G, the width of the grating pillar L_p, the height of the pillar H_p, and the distance between opposite pillars D as shown in Fig. 1. The thickness of the base plate can be adopted arbitrary value. The maximum length of the pillar, i.e., the width of the accelerator channel W, is restricted by the suppliable laser power. The accelerator is energized by the face-to-face irradiation of laser pulses in a orthogonal direction to the electron beam. 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 similar to 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. In order to accelerate the electron, the speed of the injected electron, v_0 must be tuned to satisfy $v_0/c = L_G/\lambda$, where the electric field distribution is approximated by a sine wave and c and λ are the speed of light and the wavelength of the laser, respectively. The normalized pillar height is approximated to be $H_p/\lambda \approx 1/\left(2\left(n-1\right)\right)$ by considering a path difference of π, where n is the refractive index of the pillar material [4]. The distance between opposite pillars is assumed to be $D/\lambda < 1/4$ by considering the diffraction blurring from the pillar edge. According to the reference [1], the acceleration field strength decreases by 20 percent by increasing D/λ from 0.25 to 0.5 in case of silica (SiO_2, $\epsilon = n^2 = 2.07$ for $\lambda = 1\mu m$). Accurate values of these parameters are determined with help of the numerical simulation code.

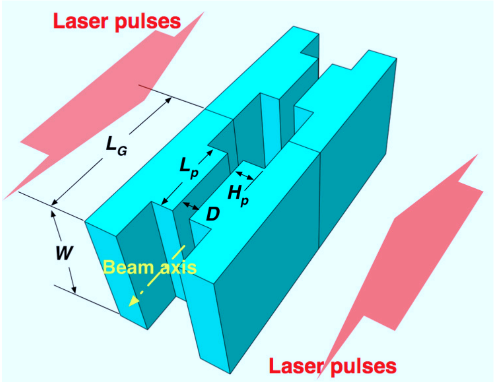

Figure 1: Schematic drawing of two periods of an accelerator unit.

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The free finite-difference time-domain (FDTD) simulation software, Meep [5] was used to know electric field distributions in PLDAs. The wavefront of the laser pule is deformed to concave shape as shown in Fig. 2(a). The boundary between the dielectric and the vacuum causes diffraction and reflection of the laser beam. The diffracted and reflected wavefronts interfere each other and make a complex pattern of field intensity. The alternate field distribution is produced if the configuration satisfies the proper condition as seen in Fig.2(b). Since the shorter L_G is desirable to reduce a restriction on designing an electron gun of the PLDA, we studied to find the minimum L_G to produce the alternate field distribution. Contour plots of the electric field in the xt-space along the center of the acceleration channel are shown in Fig.3 with world lines, trajectories in xt-space, of electrons. Electrons can be efficiently accelerated in the parameter region of $1 \geq L_G/\lambda \geq 0.5$ ($L_p = L_g/2$ is assumed), if electrons always feel the electric field of the same direction along their trajectory. In the region of smaller grating period than $L_G/\lambda < 0.48$ ($L_p/\lambda < 0.24$), the acceleration field disappears as shown in Fig.3(c). Electric field distributions along world lines of electron motion in an oscillation period of the laser field are shown in Fig. 4. The positive region and the negative region of the field $E\left(x\left(t\right),t\right)$ contribute to the electron acceleration and the deceleration, respectively. The negative component of the field might be due to adopting non-optimal values of L_G, L_p, H_p, W_G, etc. If it is difficult to increase the acceleration field at the short grating period of $L_G/\lambda \approx 0.5$, the required accelerator length become longer than that listed in Table 1.

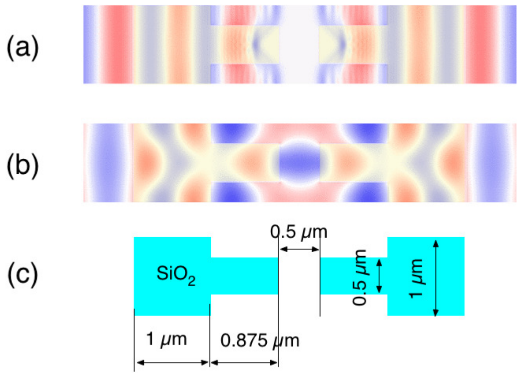


Figure 2: Simulation results of field distributions in the period of the accelerator. (a) The transient feature of the electric field distribution. (b) The steady state field distribution. (c) One unit of the accelerator made of silica. $\lambda = 1\mu$m.

ANOTHER CONFIGURATION; INSIDE-OUT

Since the original configuration of PLDA (Fig. 1) is unfavorable from the view point of the fabrication, we studied an inside-out structure as shown in Fig.5(a). The alternate electric field is also created in the acceleration channel (Fig. 5(b)). Because the structure of the acceleration channel is similar to the Fabre-Pérot etalon, $2D/\lambda = N$ is the optimal condition for producing the intense field in the accelerator gap, where N is the integer. The preliminary result shows that the alternate field disappear in the shorter grating period of $L_G/\lambda < 0.6$. The adoption of the thinner base plate may lead us better results.

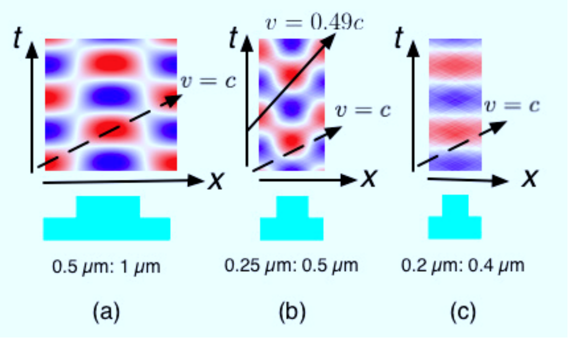


Figure 3: Contour plots of the electric field and world lines in xt-space. Arrows with broken lines and solid line indicate electron trajectorie at the speed of $v = c$ and $v = 0.49c$, respectively. (a) is at $L_G/\lambda = 1$ and $L_p/\lambda = 0.5$. (b) is at $L_G/\lambda = 0.5$ and $L_p/\lambda = 0.25$. (c) is at $L_G/\lambda = 0.4$ and $L_p/\lambda = 0.2$.

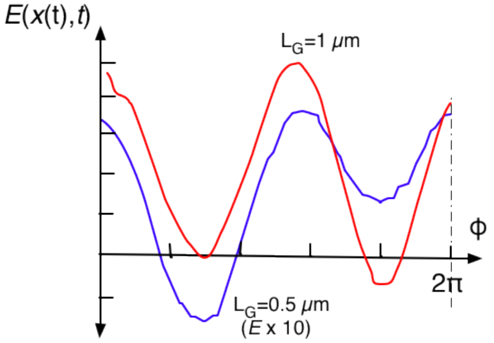
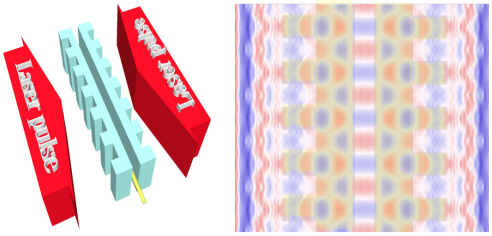


Figure 4: Electric field distributions along world lines of electrons in a period. The field strength of $L_G/\lambda = 0.5$ is expanded ten times.

LASER PARAMETERS

The irradiation intensity of the laser pulse on the surface of the dielectric material must be kept below the damage threshold value I_{th}. The required energy of the laser pulse for one side is expressed to be $E_L = I_{th} L_A^2 W / \langle v \rangle$, where L_A, and $\langle v \rangle$ are the accelerator length and average velocity of the electron, respectively. In order to reduce the required energy of the laser, the illumination area and time of the laser pulse is limited around the electron bunch by



(a) (b)

Figure 5: (a) the sketch of the inside-out structure. (b) the field strength contour map. The dielectric structure of five units is shown by the pale yellow. $L_G/\lambda = 1,\ L_p/\lambda = 0.5,\ D/\lambda = 0.5,\ H_P = 0.875$. The material is silica.

synchronizing the laser pulse with the motion of the electron bunch. If the accelerator is illuminated by sequential N pulses, the energy of each laser pulse is decreased to $E_L(N) = I_{th}L_A^2W/(\langle v\rangle N^2)$. 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 in a small space is inproper for our purpose. A fiber laser system might increase the freedom of the configuration, as shown in Fig. 6. While there are still uncertainties, parameters of the accelerateor and laser are listed in Table 1 for the ideal case.

Table 1: Parameters of the PLDA and Fiber laser. The wavelength of the laser is 1μm. Both the reflection and diffraction effects are not included.

Grating period L_G	0.5λ to 0.94λ
Initial electron energy	79 keV
Width of the accelerator channel W	0.1 mm
Length of the accelerator L_A	0.48 mm
Area of irradiation (one side) A	4.8×10^{-4} cm^2
Acceleration time τ_A	2 ps
Laser power P_L	4.8 GW
Laser energy (one side)	9.6 mJ
Pulse width τ_L	2 ps
Number of laser pulses (one side) N	5
Power of each laser pulse	950 MW
Laser energy per pulse	0.38 mJ/fiber
Total laser energy (one side)	1.9 mJ
Pulse width	400 fs

SUMMARY AND DISCUSSION

In order to develop a useful tool for the basic investigation of the radiobiology, we are studying the laser driven dielectric accelerator. From the viewpoint of the fabrication, our effort is focused on the phase-modulation-mask-type laser-driven dielectric accelerator (PLDA). The required beam energy and bunch charge, which depend on the thickness of the specimen, are in the range of 100 keV to 1 MeV and 0.1 fC to 1 fC, respectively.

The simulation results by using the FDTD simulation code, Meep, showed that the minimum grating period, was $L_G/\lambda = 0.5$ for the original configuration of PLDA provided that the accelerator structure was made of silica. The acceleration field strength at $L_G/\lambda = 0.5$ was around 10% of the value of $L_G/\lambda = 1$. Since this is the serious problem for realizing the compact accelerator with a small scale laser (see Table. 1), we are conducting the precise simulation study to fix optimal values of the structure and the laser. The optimistic value of the required total laser energy is 4 mJ for obtaining 1 MeV electron bunch.

The acceleration field was also produced by the inside-out accelerator structure. However, L_G/λ was limited to longer than 0.6 in the preliminary simulation result.

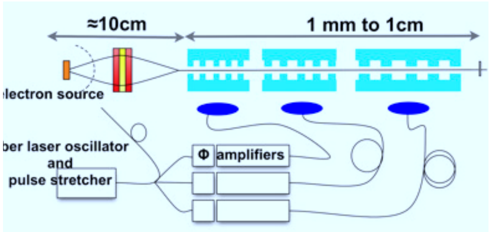


Figure 6: The conceptual drawing of the laser driven dielectric accelerator.

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