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MICROBEAM IRRADIATION SYSTEM WITH A DIELECTRIC LASER ACCELERATOR FOR RADIOBIOLOGY RESEARCH *

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Abstract

In order to realize a compact electron microbeam irradiation system, two schemes of dielectric laser accelerator (DLA) which consist of Fabry-Perot (F-P) resonators were studied by using simulation codes based on the finite-difference time-domain (FDTD) method and the rigorous coupled-wave analysis (RCWA): a multilayer F-P and a dual-grating DLA. The multi-layer F-P with an outward-facing grating enhances acceleration field in the resonator. Owing to the limitation of the image transfer of an electric field at the grating boundary by the Talbot effect, the high accelerating gradient is formed only for relativistic electrons. The amplitude of the second order component of the electric field which synchronous to sub-relativistic electrons decreased to 1/100 of that of the first order. The dual grating F-P resonator is applicable for the DLA. By utilizing the dependence of the reflectivity and the reflection phase on the dimensions of the sub-wavelength gratings, the structure of the dual grating DLA was optimized to accelerate the sub-relativistic electron. The laser required power is about 1% of the non-resonant DLA.

INTRODUCTION

In order to estimate the health risk associated with a low radiation dose, the basic radiobiological process must be clarified by irradiating a cell with a well-defined microbeam of ionization radiation, Since present microbeams are delivered by conventional accelerators, the location and the time slot for radiobiological experiments are restricted. Therefore, a laser micro-irradiation (LMI) system is widely used in the field of radiobiology because of its acceptably small size. However, a DNA damage in a cell nucleus caused by the LMI system does not necessarily simulate a radiation effect because various reagents are used to produce free radicals in the cell. If the laser of the LMI system is replaced by a small-scale accelerator such as a dielectric laser accelerator (DLA), radiobiological experiments might be performed under more realistic conditions.

In order to realize a compact system, we studied two schemes of resonator for DLA.

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COMPACT ELECTRON MICROBEAM IRRADIATION SYSTEM

Lasers for DLAs

Electron microbeams are easily obtained by using a conventional scanning electron microscope (SEM). However, the low-energy beam of the SEM has a troublesome scattering problem. In order to restrict the an expansion of the electron beam to less than 1 μm when passing through the biological cell, the energy of the electron beam must be higher than 0.5 MeV. Ultra-short laser pulses less than 100 fs are

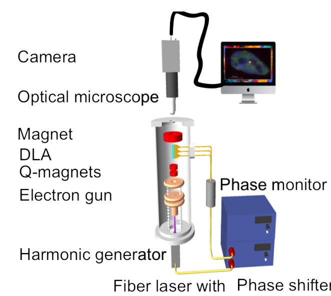

Figure 1: The concept drawing of the compact EMBI system for the radiobiology research.

widely used in DLA experiments because of the high laser induced damage threshold (LIDT) of dielectrics. However, it is rather difficult to build a compact system because it consists of large free-space optics such as an optical pulse compressor and mirror-based-optical paths. On the other hand, laser pulses with a duration longer than 10 ps can be delivered by optical fibers which is suitable for building a compact electron microbeam irradiation (EMBI) system. Actually, a commercially available fiber laser delivers 100 μJ pulse of 10 ps at the repetition rate of 100 MHz.

The desirable configuration of the DLA for the compact EMBI system is that laser pulses are transported to a dielectric structure by optical fibers and the laser energy is accumulated in the resonator of DLA. The long pulse pumping of the resonator DLA is helpful to remove useless spaces which are caused by a complex free-space optical layout, even though the acceleration channel is elongated to 100 times due to the LIDT limit. Figure 1 is a concept drawing of the compact EMBI system.

Resonators for DLA

A familiar optical cavity is the Fabry-Perot (F-P) resonator which consists of a pair of high-reflection mirrors. Since

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the length of the DLA resonator, i.e., the width of the acceleration channel is about a quoter wavelength of the laser ($d = \lambda_0/4$), the Finesse which evaluate the F-P interferometer is expressed as $\mathcal{F} \approx \sqrt{R}/(1-R)$, where R is the power reflectivity of each mirror. The relation between the quality factor Q and the Finesse is $Q = (\omega_0 d/\pi c)\mathcal{F}$. For the short cavity of $d = \lambda_0/4$, the quality factor is expressed to be $Q \approx 0.5\mathcal{F}$. When the high-Q resonator of $Q = 10000$ is pumped by the 10-ps laser pulse at the intensity of 100 MW/cm^2, the intensity of stored electromagnetic field attains the intensity of 1 TW/cm^2 in the cavity, which is about 3% of the LIDT of the 100-fs laser pulse as shown in Figure 2. The resonator-type DLA is capable of reducing the irradiation intensity to 1% of non-resonant-type DLA. There are two method to form F-P resonators such as the multilayer and the dual-grating.

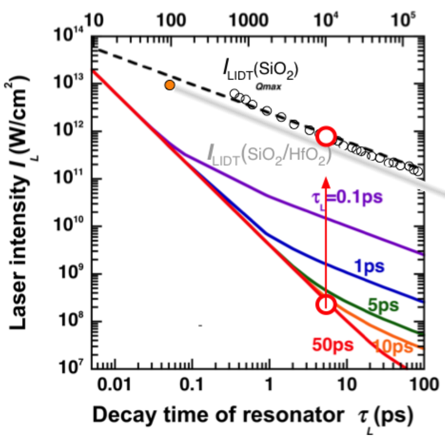

Figure 2: The energy enhancement in optical cavities is shown by the red arrow for $Q = 10000$. The broken line and the gray line are LIDTs of the bulk SiO_2 and the multi-layer mirror of SiO_2 and HfO_2, respectively.

Multi-layer mirror F-P resonator The high-reflection mirror is generally composed of multiple thin layers of different dielectric material. The reflection coefficient of 14 pairs of silica (SiO_2) and hafnia (HfO_2) layers exceeds the reflectivity of $R = 99.994\%$ and makes the resonator of $Q \approx 10000$. We proposed a combination of the binary-blazed grating and the multi-layer F-P interferometer [1]. There are two configurations of the grating and the resonator: one is that the grating is formed inside the F-P resonator, and another one is that the grating faces the outward from the F-P interferometer as shown in Fig. 3 (a). In case that the grating is located in the resonator channel, the optical cavity can not accumulate the electromagnetic energy because of a small Fresnel number (large diffraction loss) and low Q factor. On the other hand, the configuration of the outward-facing grating, the image of the electric field at the grating boundary was transferred to the center and accumulated to form the enhanced acceleration field due to the Talbot effect as shown in Fig. 3 (a) and Fig. 3 (b). The calculation was done by using the finite-difference time-domain (FDTD) simulation code. Since the Talbot length is

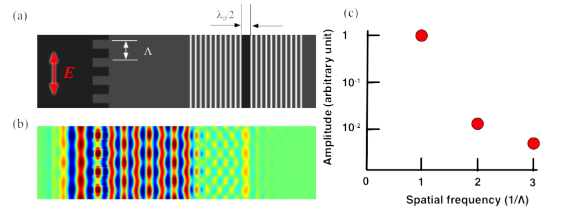

Figure 3: A structure of multi-layered F-P DLA (a), the map of the longitudinal electric field strength E_z (b) and the Fourier spectrum of E_z (c).

expressed as $Z_T = \lambda_0/\left(1-\sqrt{1-\lambda_0^2/\Lambda^2}\right)$, the smaller grating period than the laser wavelength is not allowed, where Λ is a grating period to transfer the image. Therefore, the configuration of the grating directed outward is applicable to accelerate relativistic electrons. Higher order harmonics of the field distribution would be utilized to accelerate sub-relativistic electrons. However, the amplitude of the second harmonics is about 1% of the first order amplitude as shown in Fig. 3 (c).

Dual grating F-P resonator Another configuration of the resonator DLA is to use the nature of a sub-wavelength grating (SWG), which is illustrated in Fig. 4 (a). Since the SWG acts as the high reflection mirror, SWGs have been applied as mirrors in vertical-cavity surface-emitting lasers (VCSELs), Fabry-Perot resonators, and hollow-core waveguides. We studied the possibility of application of the dual SWG to the F-P resonator and DLA. In order to enhance the accelerating gradient in a dual-grating structure, we make use of the high reflectivity feature of SWGs resonating with the zeroth diffraction order (plane wave) inside the channel and in turn enhancing the first-order accelerating mode. When using SWGs as mirrors in a dual-grating resonator, the channel width d is determined by the round-trip phase condition for the zeroth order $\phi = 2\psi_{R,0} + 2k_0 d = 2N\pi$, with N being an integer, where $\psi_{R,0}$ is the phase of the zeroth order reflection. The accelerating gradient can be enhanced by resonating the zeroth diffraction order inside the channel.

At the resonant wavelength λ, the circulating field E_c propagating downward inside the channel is related to the incident field E_i through the enhancement factor $A_c = E_c/E_i = 1/\sqrt{1-R}$ (Fig. 4 (b)). With a near-unity reflectivity, the circulating field propagating upward is given by $E_b = RE_c \approx E_c$. The calculation was done by using the simulation code based on the rigorous coupled-wave analysis (RCWA). As shown in the dispersion curve (Fig. 4 (c)), one or several waveguide-array (WGA) mode can propagate inside the SWG. In the dual-mode region ($\omega_{c2} < \omega < \omega_{c4}$), the interference of two WGA modes at the grating boundaries results in an ordered checkerboard pattern as shown in Fig. 5 (a)(b)(d)(e)(f). A high reflectivity is achieved when destructive interference is obtained at the exit boundary $x = -t$, e.g., the regions marked by the white circles in Fig. 5 (a). On the other hand, constructive interference at both the input

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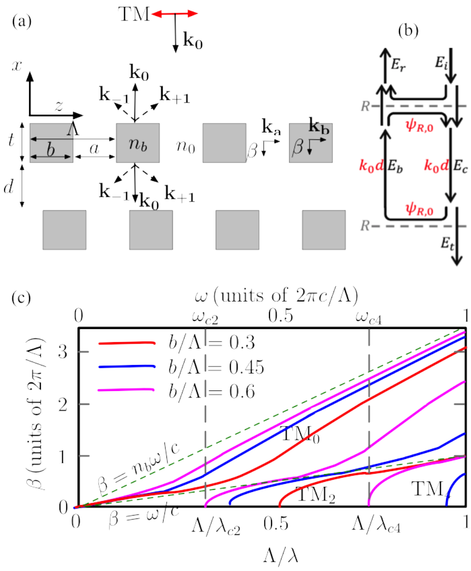

Figure 4: (a) Cross-section of a dual SWG and the wave vectors. A TM-polarized plane wave is incident from above with the electric field perpendicular to the grating bars. (b) Fields for a plane wave incident on a Fabry-Perot cavity with mirror reflectivity R and reflection phase $\psi_{R,0}$. Indicated are the electric fields (black) and phase shifts (red). (c) Dispersion curves ($\beta - \omega$) of WGA modes in an SWG. ω_{c2} and ω_{c4} are the cut- off frequencies of the TM2 and TM4 modes with $b/\Lambda = 0.6$, respectively.

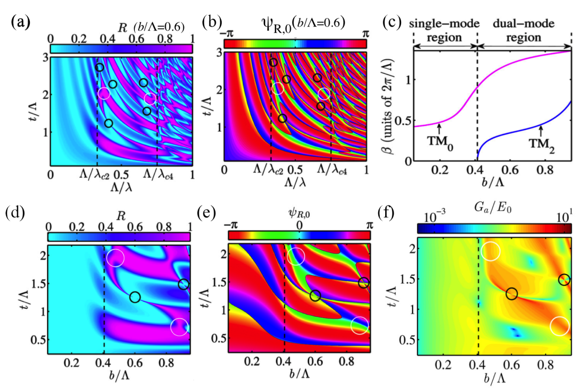

Figure 5: The t-Λ maps of the reflection coefficient (a) and the phase (b) at $b/\Lambda = 0.6$. (c) is the x-wavenumber β of WGA modes as a function of b/Λ. The x-component of wavenumber β of WGA modes as a function of b/Λ. (d)(e)(f) are t- b maps of reflectivity R), reflection phase $\psi_{R,0}$ and accelerating gradient at the grating surface G_a/E_0, respectively. The black dashed lines in (d)(e)(f) represent the boundaries between the single- and dual-mode regions. Parameters: $\Lambda = 640$ nm and $\lambda = 1550$ nm.

and exit boundaries results in a high-Q resonator with strong fields in the dielectric, which is undesirable for our purpose. With a low enhancement factor and a small channel width, the resonator can be pumped by an ultrashort laser pulse of a lower power and sustain a high accelerating gradient without damage.

Parameters of the SWG for dual grating resonator DLA for accelerating 50 keV electrons by a 1550 nm laser pulse are determined by using Fig. 5. The synchronicity condition requires a grating period of 640 nm. Figure 5(c) shows that there exist two propagating WGA modes at $b/\Lambda > 0.41$. Their interference results in ordered reflectivity and phase patterns, as shown in Figs.5 (d) and Fig. 5 (e), respectively. The t-b map of the normalized accelerating gradient G_a/E_0 at the grating surface is shown in Fig. 5 (f). Some of the high-reflectivity regions useful for DLA are marked with white circles, while some of the undesirable high-reflectivity regions with high-Q resonance in the grating are marked with black circles. The reflectivity of the SWG ranging from zero to unity as shown in Fig. 5(b) enables control on the enhancement factor and filling time, i.e. Q-factor. The choice of reflectivity is a trade-off between the enhancement factor and the achievable accelerating gradient. In order to sustain a high accelerating gradient, a low enhancement factor with an ultrashort filling time is desirable.

The highest acceleration gradient for 50 keV electrons can be attained at very narrow channel width of $d = 102$ nm with the enhancement factor of $A_c = 11.5$, the accelerating gradient at the grating surface of $G_a/E_0 = 0.197$, the laser pulse width of $\tau_L = 0.18$ ps. The laser required power is 0.76% of the non-resonant DLA.

SUMMARY

In order to realize a compact system, we studied two schemes of resonator type DLA, the multi-layer F-P and the dual grating F-P. The multi-layer F-P with the outward-facing grating enhances acceleration field in the resonator. However, due to the limitation of the image transfer by the Talbot effect, the high accelerating gradient is formed only for relativistic electrons. The dual grating F-P resonator is applicable for the DLA. By utilizing the dependence of the reflectivity and the reflection phase on the SWG dimensions, the structure of the dual grating DLA was optimized to accelerate the sub-relativistic electron. With a low enhancement factor and a small channel width, the resonator can be powered by an ultrashort laser pulse of a lower power and sustain a high accelerating gradient without damage. The laser required power is about 1% of the non-resonant DLA.

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