SILICA ROD ARRAY FOR LASER DRIVEN PARTICLE ACCELERATION*

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Abstract

Here we describe a structure of double-row silica rods array for laser driven acceleration. Similar to the dual-layer rectangular grating structure, the periodic arrangement of the rods alongside the beam channel provides the necessary phase modulation of the electromagnetic fields, and therefore required phase synchronicity for laser acceleration of charged particles. Resonances among adjacent rods could enhance the near-fields in the gap region to achieve high gradient operation. Simulation has been carried out to optimize the structure dimensions for high accelerating gradient or high acceleration factor. Results show that acceleration factor up to 0.45 could be achieved from this rod array structure. One advantage of this structure is that all the rods are fabricated on one single substrate, therefore positioned and aligned with photolithographic level precision. Several prototype samples have been fabricated for potential laser acceleration experiments.

INTRODUCTION

To utilize the extraordinary electric field available from the state-of-the-art laser systems for charged particle acceleration has long been attractive in the advanced accelerator research. Laser driven dielectric accelerator structures possess advantages over conventional metallic RF structures in their miniaturized dimensions, greatly reduced manufacturing cost, larger breakdown threshold, and higher accelerating gradient [1]. Several resonant or waveguide based structures have been proposed theoretically [1-3]. Recently, near-Infrared laser induced electron energy modulation has been demonstrated for the first time on a fused silica near-field grating structure [4], with larger than 250 MV/m gradient observed.

The dual-layer rectangular grating structure [2] is advantageous for its structural simplicity and convenience of excitation (direct side illumination). However, on-chip power network of an integrated accelerator or accelerator-based light source usually employs a high-index-material waveguide sitting upon a planar low-index substrate, where laser light travels inside the waveguide parallel to the substrate. Side illumination then implies that grating teeth needs to stand up straight with respect to the chip substrate. Direct lithographic fabrication of these vertical teeth up to tens of micron tall is challenging. To vertically assemble a dual-layer, pre-bonded grating accelerator to the chip substrate also demands much fabrication and alignment effort.

Meanwhile, deep etching of silicon to form long cylinder array on a substrate has been demonstrated feasible. Oxidation process after etching is also demonstrated to transfer these rods to fused silica. This rod array may essentially serve as the phase-resetting dielectric mask just as well as the rectangular grating structure, but already integrated since it can share the same substrate with the on-chip waveguide network. This paper explores this possibility, by looking into achievable acceleration gradient from a silica rod array structure. Parametric study results of the structure dimensions will be shown, aiming for either optimal acceleration factor or large field enhancement. Following that will be an introduction to the manufacture of the structure.

DESIGN AND SIMULATION

Figure 1 below illustrates the proposed rod array accelerator structure. Two rows of dielectric rods with radius r and length l are laid on a substrate. The two lines are separated in the z direction by a gap width w, forming the electron accelerating channel. Rods across the gap have their centre positions aligned along the y direction. Within each row, the centre-to-centre periodicity between adjacent rods is p. Laser light is incident along the z direction to power this accelerator structure.

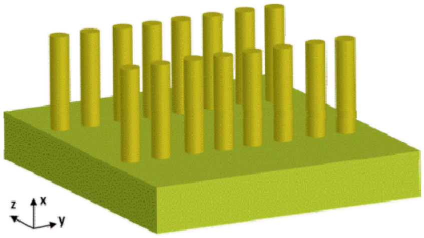

Figure 1: Layout of the rod array accelerator structure.

Silica Rod Array for Acceleration

The structure is modelled in Ansoft HFSS [5] to look for possible phase modulation for net acceleration gradient. Figure 2 shows the single-period structure simulated, with its geometrical parameters denoted on the schematic. Its y-direction periodicity is reflected by assigning master and slave boundary conditions to its left and right xz plane boundaries, with zero-degree phase delay. A plane wave excitation propagating towards the positive z direction is launched, with two perfect-matching-layer boundaries terminating the front and back xy planes to simulate infinite open spaces. The incident plane wave has its e-field polarized in the y direction, with magnitude of 1V/m. The top and bottom yz planes of the model are terminated by perfect magnetic boundary

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conditions, so that the rods (1 um long in the model) are effectively infinitely long in the x direction. The rods are made of silica with a dielectric constant of 2.40 and assumed no material loss. The periodicity p is set to 3 um, and so is the simulation wavelength. Note that the gap width $w = p/6$ is defined as the nearest rods edge distance along z, so that the centre-to-centre rod distance is $w+2r$ as marked in the figure. The rod radius is initially set to $0.456p$ in order for the plane wave to experience π extra phase shift per rod along its longest dielectric path in the z direction, so that the wave front can be recovered past the rods [2]. The inset in Fig. 2 plots the real part of the E_y component on the bottom yz surface. One can observe that the incident plane wave recovers its phase front well behind the rods. Also an enhanced field and modulated phase distribution occur in the gap between the rods, which are necessary for net acceleration after integration over one period.

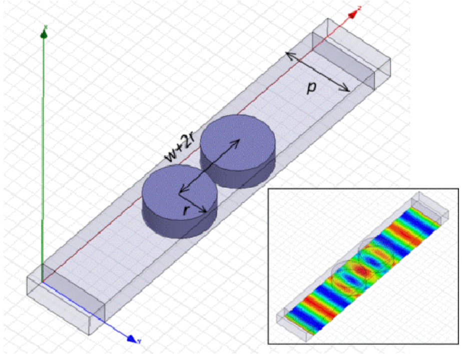

Figure 2: Simulation model of one period of the silica rod array accelerator structure. Inset is the colour map of its longitudinal y component with a plane-wave illumination.

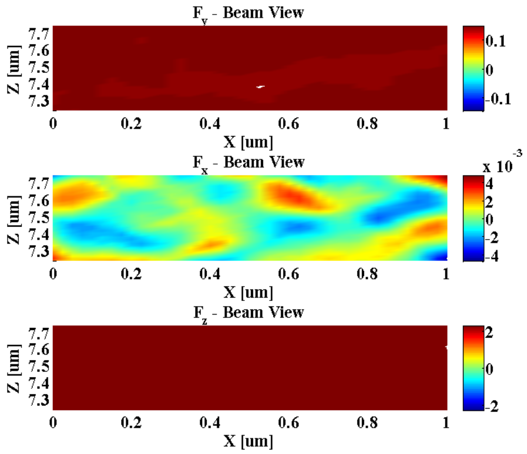

Figure 3: Integrated accelerating force F_y, and deflecting forces F_x and F_z over one rod array period, at a particle injection phase optimized for maximum F_y.

To evaluate the accelerating and deflecting forces a charged particle traversing the channel experiences, the three components E_x, E_y, and E_z in the gap region are sampled and exported. E_y at the centre of the xz cross-sectional area, offset by an extra phase Φ denoting the particle injection phase with respect to the optical phase, is then integrated over the y coordinate for one period to get $F_y(\Phi)$ as the integrated kick a particle of unit charge will encounter. Φ is then scanned over the 2π optical cycle to determine its optimal value to maximize the net acceleration F_y. E_x and E_z are then offset by this optimal injection phase, and integrated as the net deflecting kicks. Calculation results of the model in Fig. 2 are colour-mapped over the gap transverse area in Fig. 3 below. Net acceleration is indeed feasible, with quite uniform F_y of around 0.145 V/m over the whole cross-section of the channel. F_x is almost three orders of magnitude smaller, thus negligible. However, F_z is quite large – about 2.253 V/m over the transverse area, therefore this structure mainly deflects the particle in the z direction.

Elliptical Rods to Optimize Acceleration

From the inset of Fig. 2, it is clear that the dielectric path length along the longitudinal y direction needs to be further shortened to approach one half of the full sinusoidal cycle, so that ideal for maximum net acceleration [2]. With the z dimension size of the rods fixed still for the purpose of the wave front recovery, it implies that the rods need to be elliptically shaped, whose major axis radius R_z will be equal to $r = 0.456p$, and minor axis radius R_y being a variable.

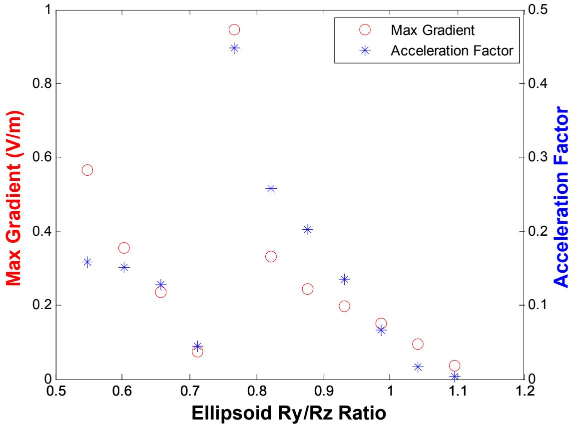

Figure 4: Maximum longitudinal gradient (red circle) and the corresponding acceleration factor (blue star), as the minor axis length of each rod in an elliptical rod array accelerator varies.

Parametric study of R_y (with $p/6$ gap width) has its results plotted in Fig. 4. The maximum gradient value is still the integrated acceleration gradient F_y at optimal injection phase. The acceleration factor (AF), as another important figure of merit (FOM) for dielectric laser acceleration, is defined as the acceleration gradient divided by the maximum e-field magnitude in the dielectric material. It measures the practical achievable gradient before the material breaks down at certain threshold field intensity. The plot shows coincident peaks of both FOMs at $R_y = 0.767R_z$, where the maximum gradient F_y is greatly improved, reaching 0.945 V/m. The optimal acceleration factor on the right ordinate is roughly 0.45. It is worth mentioning that in this case F_z is about 1.05 V/m and F_x remains negligible. Thus the longitudinal kick is of comparable magnitude with the deflection kick, also a great improvement over the circular rod array design.

Resonant Structure to Enhance Gradient

When doing the same parametric study of R_y, however with doubled gap width $w = p/3$, the elliptical rod array structure shows strong field resonance at $R_y = 0.658R_z$. In this case, with the same incident field magnitude of 1 V/m, the scattered fields from one rod and its adjacent rods interfere constructively, enhancing the longitudinal field in the middle of the gap up to 42 V/m from simulation. Figure 5 illustrates this sharp resonance, and the resultant extraordinary gradient of 17.9 V/m at the peak of the resonance. The inset figure depicts the colour map of the E_y component on the bottom surface of the model, much stronger in magnitude than the excitation plane wave. However, the inset also shows enhanced fields at spots inside the silica rods, normalizing the large gradient to mediocre AF values of 0.311 maximum and 0.267 at the resonance peak.

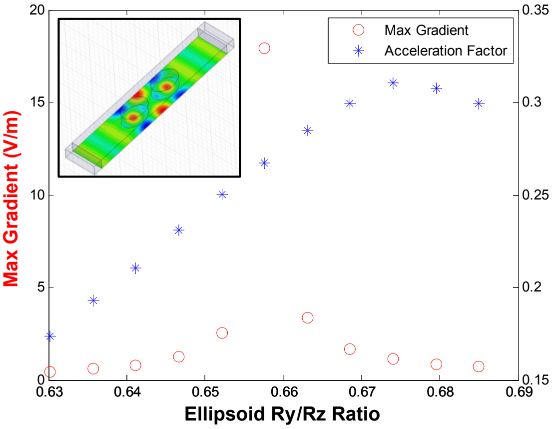

Figure 5: Maximum gradient (red circle) and the corresponding AF (blue star) of a resonant elliptical rod array design.

Despite the fact that its AF is not outstanding, with much smaller excitation field this resonant design could yield the same accelerating gradient as that of non-resonant designs. Therefore it could be operated at low laser power level. Also, at resonance the other two components E_x and E_z remain unenhanced, and the integrated deflecting kick F_z is only 1.8 V/m, almost one order of magnitude lower than the longitudinal kick. F_x is three orders of magnitude lower than F_y. This resonant design deflects charged particles much less, and uses laser energy more efficiently on acceleration.

FABRICATION

The adopted strategy to make this silica rod array structure is to first fabricate the rods in silicon and then convert the rods into silicon dioxide. It takes advantage of the available deep etch chemistry for silicon while avoiding the difficulty in fabricating high-aspect ratio silicon dioxide rods. A 600 nm thick negative tone resist, Hydrogen SilsesQuioxane (HSQ), was spun on a silicon wafer and subsequently exposed by an electron-beam lithography tool at 100 kV acceleration voltage. After development the pattern was transferred to silicon in a high-density plasma etching tool using chlorine chemistry. The etched depth was about 10 micrometers. The conversion into silica rods was achieved through wet oxidation at around 900 degree C.

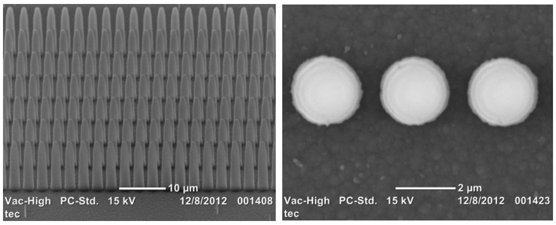

Figure 6: Side-view and top-view SEM images of a fabricated silica rod array structure.

SEM images of some prototype samples of a silica rod array structure are shown in Fig. 6. From the top view on the right, the circular shapes are well defined, and the centre-to-centre spacing of the rods is roughly 3 um. From the side view on the left, the rods have consistent heights of around 10 um. However, instead of a uniform cylinder, each rod exhibits a tapered down diameter along its long axis. A silicon-made rod array may provide net acceleration just as well, whose manufacture then avoids the oxidation process and may lead to better control on the rod cross-sectional uniformity. Fabrication of elliptical shaped rods array is also under exploration.

CONCLUSION

In this work, a new accelerator structure of double-row silica rod array is studied. Net acceleration is found achievable with circular shaped rods, and elliptical shaped rods improve its performance in terms of optimized acceleration factor and reduced deflecting forces. Acceleration factor as high as 0.45 can be realized with an ellipse aspect ratio of 0.767. Of certain dimensions the structure also exhibits strong longitudinal e-field enhancement in the accelerating channel, therefore useful for achieving large gradient with low laser power, and for suppressing beam deflection. Preliminary fabrication of a circular shaped rod array has been done. Samples appear promising, and show room to improve with respect to the uniformity of the rod cross-section, as well as possibility to fabricate elliptical shaped rods.

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