DESIGN OF ADVANCED PHOTONIC BANDGAP (PBG) STRUCTURES FOR HIGH GRADIENT ACCELERATOR APPLICATIONS*

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Abstract

The design of advanced photonic bandgap (PBG) accelerator structures is examined. PBG structures are chosen for their wakefield damping. A potential disadvantage of PBG structures, as well as damped detuned structures, is the increased wall currents at the structure surface due to the reduced surface area, leading to higher pulsed wall heating. Research is carried out to improve the pulsed heating performance of PBG structure concepts while maintaining higher order mode damping. Wakefield damping parameters are discussed and a quantitative figure of merit is expressed to evaluate and compare PBG concepts. Pulsed heating performance in PBG structures is improved by breaking perfect symmetry and allowing deformation of both rod and lattice geometry. A final design for an improved pulsed heating performance PBG structure for breakdown testing at 11.424 GHz is presented and discussed.

INTRODUCTION

Damped structures are necessary for the next generation of linear accelerator concepts. Photonic bandgap (PBG) structures are an alternative to conventional pillbox structures that can provide wakefield damping. PBG structures have been demonstrated in proof of principle experiments [1]. A PBG structure has also been tested for breakdown performance [2]. Simulations and experiments have revealed the need for improved pulsed heating performance in these structures, while maintaining wakefield damping properties.

The general transverse wake potential, $W_\perp$, can be written as a sum over cavity modes, n, and a function of the mode kick factor, $k_{\perp n}$, mode frequency, ω_n, mode quality factor, Q_n, and the distance from the exciting charge, s, as shown in Eq. 1.

$$W_\perp(s) = \sum_n 2k_{\perp n} e^{-\frac{\omega_n s}{2Q_n c}} \sin\frac{\omega_n s}{c} \qquad (1)$$

Wakefield damping is achieved by reducing this wake potential, so that bunches subsequent to the exciting bunch are not significantly disrupted. Damping can be achieved by reducing the magnitude of the potential, but also by increasing the loss of unwanted modes, so that they damp rapidly in time or bunch separation.

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The peak temperature rise due to pulsed heating, ΔT, can be expressed as a function of the surface material resistance, R_S, thermal conductivity, K, and thermal diffusivity, D, the rf pulse length, t_P, and the maximum surface magnetic field, H_{peak}, as shown in Eq. 2 [3].

$$\Delta T = \frac{R_S}{K}\sqrt{\frac{Dt_P}{\pi}}|H_{peak}|^2 \qquad (2)$$

For accelerator applications the achievable gradient, or surface electric field for a given pulsed heating temperature rise, or peak magnetic surface field is of interest. The ratio of maximum surface electric field to maximum surface magnetic field (E/H [Ω]) is used throughout this paper as a reference for comparing the pulsed heating performance of different structure designs.

SIMULATIONS

Eigenmode *HFSS* simulations allow mode properties to be determined for both the fundamental, TM_{01} mode, and first higher order mode, the TM_{11} dipole modes. The simulations were simple two-dimensional representations of PBG structures to allow for fast tuning of cavity parameters. In two-dimensions, the fundamental mode frequency becomes 10 GHz for what in three-dimensions is a 11.424 GHz structure, such as that reported in [2]. Simulations were made with ohmic loss on structure surfaces, and perfectly matched layer boundaries to represent diffractive loss. A structure with two rows of rods was simulated. The two parameters of the structure are the rods radius, a, and rod spacing, b. One of these is fixed to tune the fundamental frequency, leaving only one free parameter, the a/b ratio.

The structure properties can be observed as functions of a/b as a/b is varied. As the a/b ratio is changed, $k_\perp$ is not observed to vary more than is attributable to *HFSS* field convergence. Only the higher order mode (HOM) Q factors are observed to vary strongly as a function of PBG design parameters. The fundamental mode Q also varies. This can be seen qualitatively in Fig. 1. The fundamental mode becomes slightly more confined by larger rods, videlicet larger a/b. The dipole modes also become more confined with increasing a/b.

RESULTS

As the a/b ratio is increased in a triangular lattice PBG structure, the E/H ratio improves linearly, as shown in Fig. 2. This improvement in ratio means an inverse quadratic decrease in pulsed heating temperature rise for

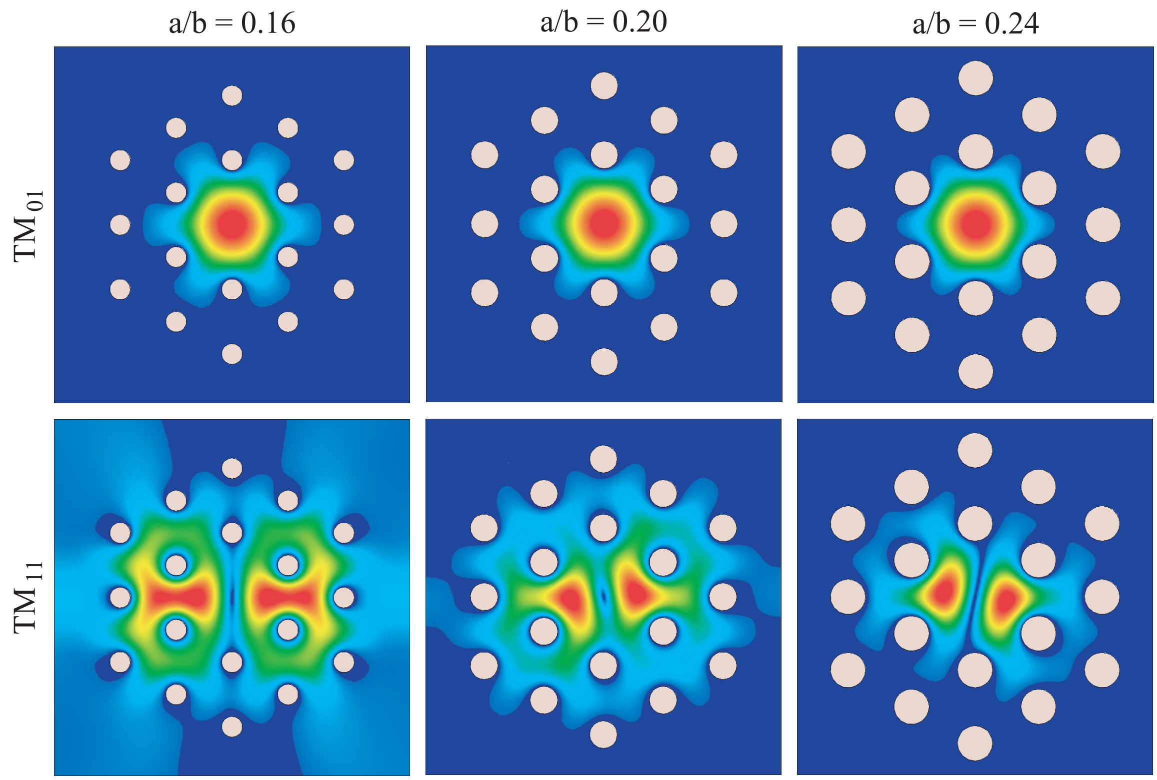

Figure 1: Electric field magnitude from *HFSS* simulations of PBG structure fundamental and dipole modes for a/b ratios of 0.16, 0.20, and 0.24.

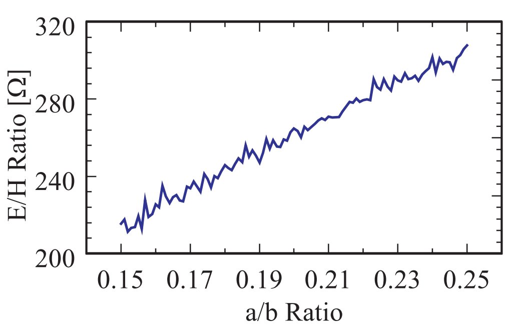

Figure 2: E/H ratio as a function of a/b ratio.

a given gradient, as motivated in Eq. 2. The inevitable byproduct of this improvement in pulsed heating performance is a decrease in HOM damping, as demonstrated by an increase in HOM Q. The Q for the fundamental and dipole modes is shown as a function of the a/b ratio in Fig. 3. Larger rods, or increasing a/b improves the mode Qs, but of specific interest is the ratio of Qs, which enable a comparison on the change in damping. The ratio of fundamental Q to dipole Q is shown in Fig. 4. A clear maximum is seen favoring an a/b ratio of ~0.17.

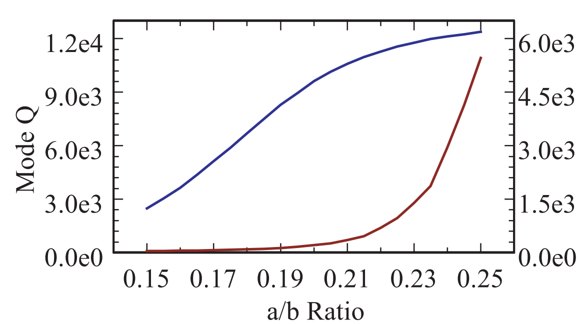

Figure 3: Q of fundamental mode (blue, left axis) and dipole mode (red, right axis) as a function of a/b.

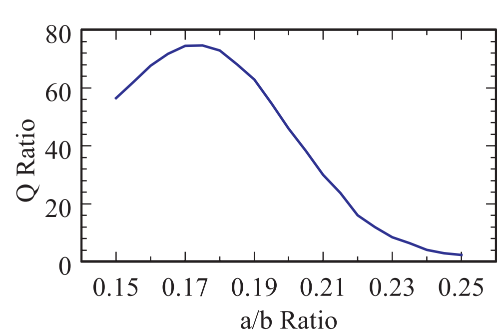

Figure 4: Ratio of fundamental to dipole mode Q as a function of a/b.

Table 1: Elliptical Rod Structure Simulation Results

Ellipticity a_{major}/a_{minor}	E/H [Ω]	TM_{01} Q	TM_{11} Q
1	285	598	40
1.25	335	1328	94
1.5	383	3125	283
1.66	397	5523	686
1.75	405	7046	1101

Table 2: Final Design Values for Elliptical Rod PBG Structure

Design Parameters	
Outer Rod Radii	2.266 mm
Rod Spacing	12.588 mm
Major Radius	3.399 mm
Minor Radius	2.266 mm

PERTURBATIONS

A great deal of symmetry is present in triangular lattice PBG structures, which constrains the large number of possible degrees of freedom to just one variable: the a/b ratio. The first row of rods experiences the highest surface magnetic field, and is the most sensitive to perturbation. Larger rods allows an improvement in E/H, but at the cost of improving the dipole mode Q. Perturbations on the inner row of rods also can improve E/H, but without decreasing the HOM damping of the structure as strongly.

The most promising of these cavity perturbations, which has been designed as a single cell breakdown structure, after [2], takes advantage of elliptically contoured rods. Only the inner row of rods affects the E/H ratio, and so only the inner row of rods is elliptically contoured. The simulation results from elliptical rod design simulations are shown in Tab. 1. An ellipticity of 1.5 is sufficient to reduce heating on the inner row of rods significantly. A full three dimensional structure design reduces the peak surface magnetic field for an accelerating gradient of 100 MV/m from 890 kA/m to 700 kA/m, so that a pulsed temperature rise of 78K for 100 ns pulse is reduced to 48K. The full breakdown structure is shown schematically in Fig. 5. The properties for this structure are summarized in Tab. 2.

CONCLUSIONS

PBG structure optimization must be sensitive to improving cavity performance without significantly impacting the damping properties for which the PBG structure has been chosen. Damping can be quantitatively gauged by HOM Q values. The optimum a/b ratio for E/H ratio performance is as high as possible. The optimum a/b for Q ratio is 0.17. An elliptical rod PBG structure has also been designed, which improves the E/H ratio, and has less pulsed heating than the previous structure [2].

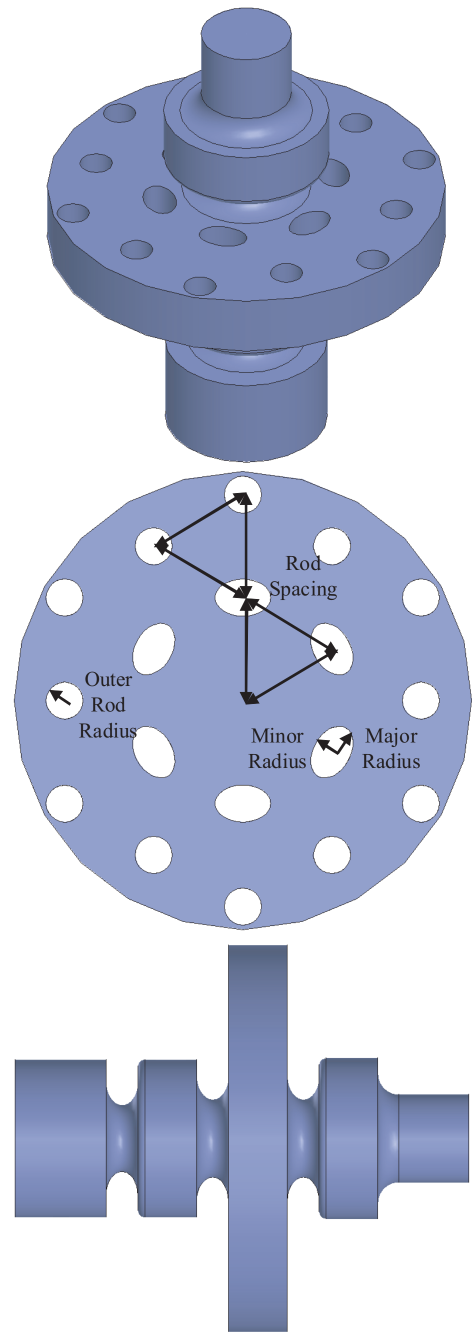

Figure 5: Elliptical rod PBG structure for breakdown testing at SLAC.

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