PHOTONIC BANDGAP (PBG) ACCELERATOR STRUCTURE DESIGN*

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Abstract

The damping of wakefields is a critical issue in high gradient accelerators operating at high frequency. It is also very important in the next generation of accelerator structures. Photonic band gap (PBG) structures have uniquely motivated damping properties, and offer significant wakefield damping. The goal of this work is to quantify the higher order mode content of a constructed metallic PBG accelerator structure, and to provide direction for future structure design. Simulations are supported by experiments currently being performed to directly measure wakefields in a 6 cell PBG structure. Future design work will focus on a structure to be cold tested, tuned, and processed to high gradient operation at the MIT Haimson 17 GHz high gradient acceleration lab.

INTRODUCTION

Wakefield damping is an important consideration in accelerator structure design. Photonic crystals are an appealing theoretical starting point for a damped structure. The frequency dependent properties of photonic crystals make it possible to form the confining wall of an accelerator structure such that a fundamental, operating mode is confined, but higher order modes, which are of higher frequency are not. The use of a metallic photonic band gap (PBG) structure as an accelerator was first proposed in [1], and designed with an analysis of actual wakefield damping and cavity performance in [2]. Such a structure was built, cold-tested, tuned, and then hot-tested, demonstrating 35 MV/m acceleration at the MIT 17 GHz high gradient acceleration lab [3, 4].

Following demonstration of acceleration, the specific wakefield damping parameters of the structure are of interest. Experiments are being performed, and preliminary results are reported in [5] to directly observe wakefield radiation produced by passing an electron beam through the unpowered 6 cell structure. In order to predict the power lost by the beam into the structure, HFSS simulations were performed to calculate the longitudinal loss factors for various modes. The PBG structure is made up of a triangular lattice of cylindrical rods, with a one rod defect; end plates are flat metallic plates with beam holes, or irises. Design parameters are summarized in Table 1. In actual experiments, there is no outer wall. In simulations a boundary must be used. For the PBG lattice, the boundary can be a large metallic outer cylinder or an absorbing outer layer. When a metallic cylinder is used, higher order modes can appear to be supported by the structure, but are not localized near the beam. HFSS simulations have been initiated with boundaries that approximate the actual experiments, in which higher order modes are free to escape the open outer wall of the structure.

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Table 1: Dimensions and design properties of the PBG accelerator structure

Rod radius	1.04 mm
Rod spacing	6.97 mm
Cavity length	5.83 mm
Iris radius	2.16 mm
Iris thickness	1.14 mm
TM_{01} frequency	17.14 GHz

SIMULATIONS

Initial simulations showed higher order modes confined in the PBG structure that were not localized to the defect, but distributed throughout the structure. It is believed that these higher order modes are only confined by the outer metallic boundary, and not by the PBG lattice.

Metallic Outer Boundary Simulations

Longitudinal loss factors, k [V/C] are calculated using Eq. 1 from [6], and the HFSS field data from the simulation of interest. The path that V_b is calculated along is varied in some cases, and is listed in mm of offset.

$$k = \frac{V_b^2}{4U} = \frac{\omega}{4}\frac{R}{Q_0} = \frac{\left|\int E_z(z)e^{i\frac{\omega z}{c}}dz\right|^2}{2\int(\epsilon_0 E^2 + \frac{1}{\mu_0}B^2)dV} \qquad (1)$$

According to PBG theory, any modes above ~20 GHz should be propagating modes, that are only confined by the metallic outer boundary of the computation region. These modes are not confined within the defect, where the beam holes are, and where they can affect the beam strongly, but they are supported by the lattice when an artificial metallic boundary is used in simulation. Longitudinal loss factors were calculated and compared with a pillbox cavity with the same irises as the PBG structure. A comparison is shown in Table 2.

Because the fundamental mode is primarily confined by the innermost rows of rods, whereas all higher order modes exist within the entire lattice, a unique damping solution is

Table 2: Summary of loss factors for existing PBG structure, and pillbox.

Mode	Parameter	PBG	Pillbox
TM_{01}	f [GHz]	17.2	17.2
	k [V/C]	$3.4 \cdot 10^{12}$	$3.6 \cdot 10^{12}$
TM_{11}	f [GHz]	23.0	25.3
1 mm offset	k [V/C]	$9.5 \cdot 10^{10}$	$4.0 \cdot 10^{11}$
2.16 mm offset	k [V/C]	$5.1 \cdot 10^{11}$	$2.0 \cdot 10^{12}$

available. Lossy outer rows of rods will perturb the operating mode very little, while significantly decreasing the quality factors of higher order modes. A simulation in which the inner row of rods are copper, and the outer two rows are stainless steel reduced the TM_{01} ohmic Q from 4400 to 3700, while reducing the TM_{11} ohmic Q from 2300 to 700. Results are encouraging.

Perfectly Matched Layer Simulations

In order to study the diffractive Q of the higher order modes, HFSS simulations were run for an outer boundary that more closely resembles that of the experiment, which is open. This was done using a perfectly matched layer (PML). A first PML result is shown in Fig. 1. The axial electric field strength is shown for the TM_{01} dipole mode, at 23.0 GHz. The field strength is localized to the lattice, away from the beam, and very high diffractive loss has been observed, giving diffractive Q's on the order of $\sim$100.

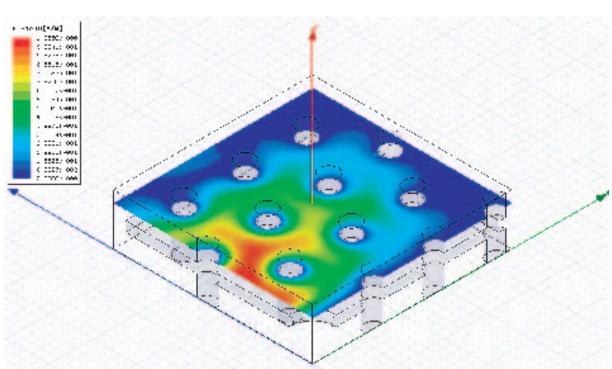

Figure 1: First HFSS simulation with a perfectly matched layer (PML) boundary. The model is one quadrant of the full PBG structure cell. The axial electric field magnitude is shown for the dipole mode. Very low diffractive Q has been observed, of order $\sim$100.

PML simulations give results much closer to the experimental situation, and provide a realistic way of examining the higher order mode content of PBG structures. Damping added to the periphery of the PBG lattice will accomplish a further decrease in the effect of these modes.

6 CELL COLD TEST

Because a 6 cell PBG structure exists, cold-testing provided an immediate basis for some experimental test of the existence of higher order mode confinement in the structure. The 6 cell traveling wave structure was connected to an Agilent E8363B Precision Network Analyzer (PNA). The measured S_{21} parameter is shown in Fig. 2 for the open structure without damping, in red in Fig. 2A, and with external damping, in blue in Fig. 2B. The mode structure is rather complex because there are many modes and because of resonances in the PNA SMA cables. Modes were distinguishable in both S_{21} and S_{11} measurements at roughly the following frequencies: 17.14 (fundamental operating mode), 23.3, 24.5, 25.7, and 26.7 GHz. The high frequency modes (23-27 GHz) have not yet been identified, but are near the dipole mode frequency of 23.0 GHz. The structure is a 6 cell traveling wave structure, so that the S parameters of the modes observed appear very broad.

Though the higher order modes are excited with very high insertion loss, they are resonant, but with very low quality factors. External damping with an absorber at the outer boundary of the structure can significantly decrease the observed modes, as shown by the blue S_{21} curve in Fig. 2B. As observed in simulations, damping in a PBG structure can be quite effective, but it must be used.

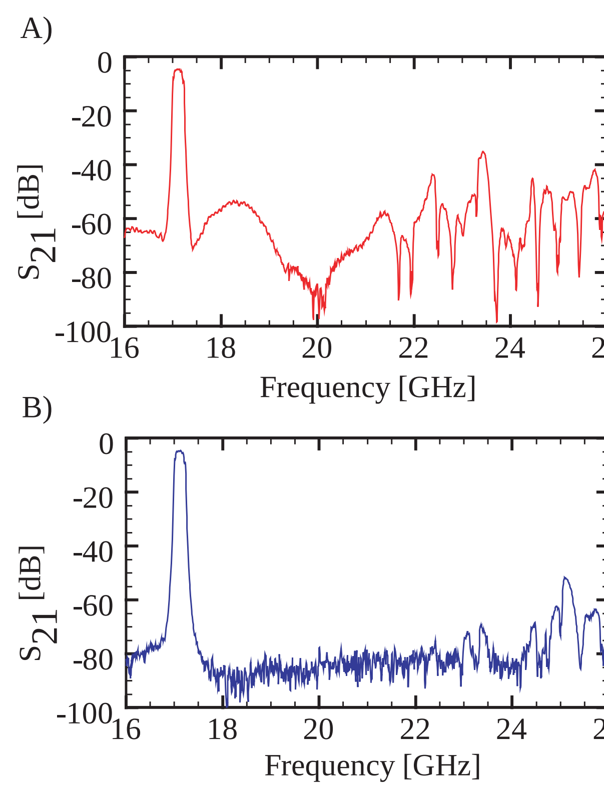

Figure 2: 6 cell metallic PBG accelerator structure S_{21} measurement. A is S_{21} in red without damping, B is S_{21} in blue with external damping. Modes are observed at: 17.14, 23.3, 24.5, 25.7, and 26.7 GHz.

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DISCUSSION

Higher order modes are seen to exist in PBG accelerator structures with very high diffractive loss, giving rise to very low quality factors. This has been demonstrated in simulations, and confirmed by cold test of the existing 6 cell metallic PBG structure. These modes are not confined near the beam holes of the structure, but throughout the lattice of metallic rods. The non-localized character of the higher order modes reduces their coupling to the beam, as seen in reduced longitudinal loss factors as compared with a standard pillbox structure. Damping can be easily applied to the outside of the structure, which reduces the higher order modes significantly. Damping can also be built into the structure design, by adding lossy rods, for example.

Further simulations are currently being run using a perfectly matched layer (PML), to simulate the open boundary of a real PBG structure. These simulations will give a better idea of higher order mode properties, and how they should be damped in real structures. Future plans entail the construction of a longer, $\sim$20 cell PBG accelerator structure with a group velocity between 0.03c and 0.05c. This long structure will include the wakefield damping that is developed by this series of simulations, and will be tested at the MIT Haimson Research Corporation 17 GHz high gradient acceleration lab.

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