

# DESIGN OF PHOTONIC BANDGAP (PBG) ACCELERATOR STRUCTURES WITH REDUCED SYMMETRY\*

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## Abstract

The design of a new photonic bandgap (PBG) accelerator structure based on a pentagonal array of rods is presented. The goal of this structure is to damp the higher order modes (HOMs) present in the structure. By removing the bilateral symmetry present in the four and six rod PBG structures the five rod photonic quasi-crystal (PQC) structure is able to damp the symmetric dipole mode. The field pattern and mode  $Q$  factors for the fundamental and dipole modes are presented for various values of the ratio of rod radius to rod spacing. These results are compared to the equivalent results for the six rod structure. The ratio of the  $Q$  factors is also calculated, and found to show an optimal value near a rod radius to rod spacing ratio of 0.17 in both cases.

## INTRODUCTION

Designs for future accelerator concepts will have to incorporate wakefield damping to be viable. This damping can be achieved via the use of photonic bandgap (PBG) structures. The breakdown and damping performance of PBG structures has been demonstrated [1, 2]. These structures show general damping of all higher order modes (HOMs). Simulations have indicated, however, that the HOM of most interest is the bilaterally symmetric dipole mode. This paper investigates the change in dipole mode damping when the conventional PBG design symmetry is modified to remove this symmetry, resulting in a photonic quasi-crystal (PQC) structure. For convenience this work refers to the five rod structure as the PQC structure, and the six rod structure as the PBG structure. Previous work on PBG structures with reduced symmetry was done by C. Bauer et al. [3].

In this context damping refers to decreasing the general transverse wake potential,  $W_{\perp}$ , given by

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

where  $n$  are the cavity modes,  $k_{\perp n}$  is the mode kick factor,  $\omega_n$  is the mode frequency,  $Q_n$  is the mode quality factor, and  $s$  is the distance from the exciting charge. Damping for PBG and PQC structures is achieved by decreasing the mode  $Q$  for the higher order modes, thus the  $Q_n$  are the parameters of interest in new designs.

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## DESIGN

The five rod PQC design began by modifying the existing six rod PBG structure to remove the bilateral symmetry. The five rod structure was chosen over a seven rod structure in order to minimize confinement of the HOMs in the defect. Thus a regular pentagon of five rods was chosen as the PQC design to be investigated. The five rod schematic is shown in Fig. 1, and values for the relevant parameters are shown in Table 1.

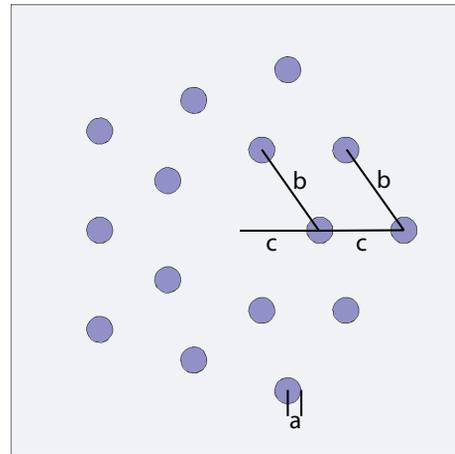


Figure 1: Schematic of five rod PQC design.

Table 1: Design values for five rod PQC structure at  $a/b = 0.170$  for a frequency of 10 GHz.

Rod Radius, $a$	2.43 mm
Rod Spacing, $b$	14.27 mm
Radial Spacing, $c$	12.14 mm

This pentagonal row of rods has three relevant dimensions: the rod radius,  $a$ , the rod spacing between the center of two adjacent rods,  $b$ , and the radial distance from the center of the defect to the center of any rod,  $c$ . Values for these dimensions are shown in Table 1. Note that these dimensions are not independent:  $b$  and  $c$  are geometrically related by  $c = \frac{1}{2}b \sec(54^\circ)$ . This relation between  $b$  and  $c$  means that there are effectively only 2 parameters for both the PBG and PQC structures. In both structures one of these dimensions is used to fix the frequency of the structure, leaving only  $a/b$  as a free parameter. For the five rod structure the ratio  $a/c$  could be used as the free parameter;  $a/b$  is used instead because the rod spacing is expected

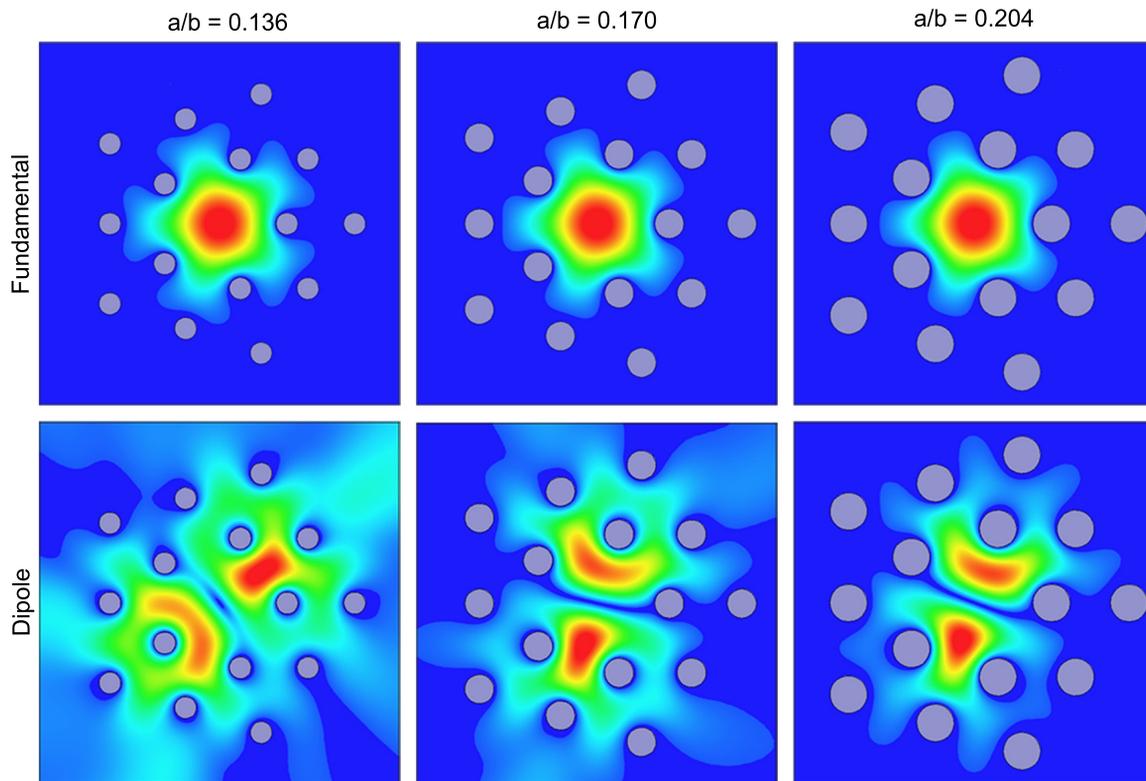


Figure 2: Electric field magnitude plots from *HFSS* simulation results of the five rod PQC for  $a/b$  ratios 0.136, 0.170, and 0.204.

to determine the mode confinement behavior, which is the behavior of interest.

The five rod structure is based on two concentric regular pentagons of rods, with an increasing number of rods in each row. Because a single row of rods is insufficient to contain the fundamental mode, the second row of rods must be placed such that the rods on the faces of the larger pentagon are aligned with the gaps between the rods at the vertices of the inner pentagon. This results in a design that looks like concentric regular pentagons where the vertices are collinear, as seen in Fig. 1. This design showed good confinement of the fundamental mode when the second row of rods was placed such that the radial distance to the vertex rods was  $2c$ . We find that two rows of rods are sufficient to contain the fundamental mode.

## SIMULATIONS

Eigenmode *HFSS* simulations were used to determine mode properties of both the fundamental mode and the dipole mode. The simulations were done in two dimensions to allow for fast tuning of design parameters, as in [1]. All simulations included ohmic loss on structure surfaces, and used perfectly matched layer boundary conditions to represent the diffractive loss present in an open structure.

As the  $a/b$  ratio is varied qualitative changes in the confinement of both fundamental and dipole mode can be seen, as shown in Fig. 2. Increasing  $a/b$  can be seen to increase

the confinement for both modes.

There are two distinct dipole mode for the PQC structure, shown in Fig. 3. One mode shows asymmetry introduced by the five rod nature of the structure. The other mode, however, is bilaterally symmetric about an axis bisecting one of the rods. Because any structure based on concentric rings of regular polygons is bilaterally symmetric about an axis bisecting a rod, this symmetric mode will always be present in a structure based on concentric polygons. The damping seen is therefore a positive result for the PQC.

## RESULTS

As shown in Fig. 4, increasing  $a/b$  increases both the  $Q$  of the fundamental and the average  $Q$  of the two dipole modes of the PQC structure. The  $Q$  of the fundamental mode begins to saturate at high  $a/b$ . The same saturation is not seen for the  $Q$  of the dipole mode. This leads to a peak in the ratio of  $Q$ s. This ratio of  $Q_{fund}/Q_{dipole}$  describes the relative damping between the fundamental and dipole modes. Of interest is how much the dipole mode can be suppressed while keeping the  $Q$  of the fundamental acceptably high, hence the peak in the ratio of the  $Q$ s in Fig. 5 is an optimal operating point for this metric.

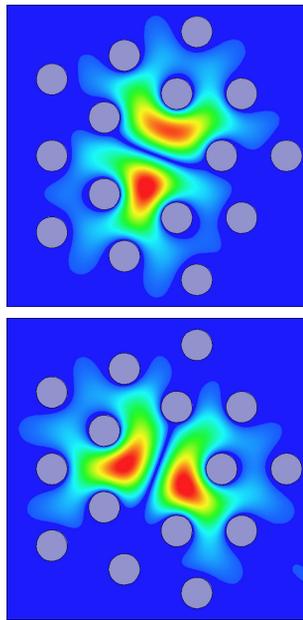


Figure 3: The symmetric and asymmetric dipole modes of the PQC shown for  $a/b = .204$ .

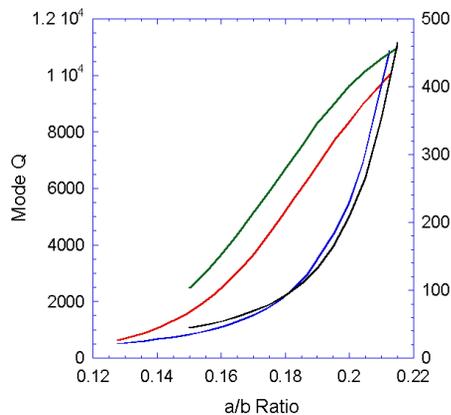


Figure 4:  $Q$  of the 5 rod fundamental (red, left), 6 rod fundamental (green, left), average 5 rod dipole (blue, right), and 6 rod dipole (black, right) modes as functions of the  $a/b$  ratio. Both the PBG and PQC structures have two rows of rods.

### COMPARISON

While an optimal operating point for the five rod PQC has been found, the results should be compared to those for the six rod PBG structure. As seen in Fig. 4, the fundamental mode  $Q$  factor for the five rod structure is lower than the fundamental mode  $Q$  factor for the six rod structure for all  $a/b$ . Because the dipole mode  $Q$  factor is higher for the five rod structure at large  $a/b$ , the ratio of the  $Q$  factors is lower for the five rod structure than the six rod structure at all  $a/b$  by about 20% at the peak. Thus the PQC structure shows inferior damping of the  $Q$  factors relative to the PBG at all  $a/b$  values. This does not necessarily mean that the

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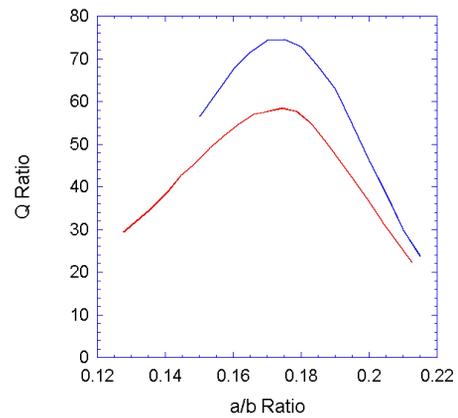


Figure 5: Ratio of the 5 rod and 6 rod fundamental  $Q$  over the dipole  $Q$  as a function of  $a/b$  ratio showing peak near 0.17.

transverse wake potential is larger for the PQC structure, as other parameters in Eq. 1 may also differ between the two designs.

The results shown in Fig. 2 strongly indicate that  $k_{\perp}$  for the PQC structure is different from  $k_{\perp}$  for the PBG structure, meaning that the scale of the wake potential would be different between the two structures. This allows for the wakefield damping of the two structures to differ from the relative performance of the  $Q$  factors for the two structures. The actual difference in wake potential is not yet known, as  $k_{\perp}$  has not yet been calculated for the PQC structure. Because the symmetry constraints of the PBG are removed in the five rod PQC it is also possible that the design could be optimized to reduce both  $Q$  and  $k_{\perp}$  for the dipole mode.

### CONCLUSION

The fundamental goal of PBG structures is to damp the wake potential while still providing good accelerating gradient. A five rod PQC structure was simulated to reduce the dipole mode  $Q$  without adversely affecting the fundamental  $Q$ . A metric was found based on the ratio of the fundamental and dipole  $Q$  factors to determine the optimal  $a/b$  ratio. The PQC structure was found to have a ratio of  $Q$  factors that is approximately 20% lower than the ratio of  $Q$  values for the six rod structure, but further work needs to be undertaken to determine whether the PQC structure in fact displays better wakefield damping, despite lower  $Q$  values.

### REFERENCES

- [1] R. A. Marsh, et alia, PAC 2009, WE6RFP081.
- [2] E. I. Smirnova, et alia, Phys. Rev. Lett. 95, 074801 (2005)
- [3] Carl A. Bauer, Gregory R. Werner, John R. Cary, JAP 104(5):053107 2008