DESIGN AND COLD TEST OF A 17 GHz OVERMODED HYBRID PBG ACCELERATOR CAVITY*

JieXi Zhang†, Alan M. Cook, Brian J. Munroe, Michael A. Shapiro, Richard J. Temkin
MIT PSFC, Cambridge, MA 02139, USA

Abstract

An overmoded hybrid Photonic Band Gap (PBG) structure used as an accelerator cavity has been theoretically designed. The PBG structure consists of a triangular lattice of dielectric (sapphire) and metallic rods. The birefringence of the sapphire affects the PBG eigenmodes and must be taken into account. The PBG cavity formed by rods in between two copper plates will be operated in a TM_{02} mode at 17 GHz. Arrangement of the rods for higher-order-mode (HOM) damping demonstrates high frequency selectivity. Comparison with a disk-loaded waveguide (DLW) cavity gives a perspective of the dielectric PBG structure operated at an accelerating gradient of 100 MV/m. Cold test of a single hybrid PBG cell presents a high-Q resonance at 17 GHz. A standing-wave (SW) hybrid PBG structure will be tested in TM_{02} mode at 17 GHz.

INTRODUCTION

A periodic photonic structure, whose dispersion relation has photonic band gaps (PBG), can be applied to accelerators due to its good frequency selectivity [1]. A travelling-wave (TW) multi-cell metallic PBG structure has demonstrated successful acceleration of electrons with gradient of 35 MV/m [2]. More SW metallic PBG structures have been studied with high power breakdown tests at both SLAC and MIT [3, 4].

A theoretical study of a dielectric PBG structure was presented by Shapiro et al. [5]. A detailed design with isotropic sapphire rods using the commercially available code Ansys High Frequency Structure Simulator (HFSS) was reported in PAC11 [6]. The dielectric band gap allows a TM_{02}-mode operation without competing with the lower-frequency TM_{01} mode since the latter is not supported in the band gap. The TM_{02} mode helps in geometry design for a high frequency of 17 GHz and mitigates the central high field away from the innermost rods. Simulations showed an accelerating gradient of 100 MV/m with lower magnetic field than the metallic PBG structure, which may reduce the breakdown rate in high power testing. A sapphire rod structure was previously built and cold tested but not tested at high power [7].

In this paper, we analyze a sapphire PBG periodic unit cell with an anisotropic (birefringent) dielectric constant. 2D cross-section design in HFSS will give an optimal configuration of a hybrid PBG structure containing both dielectric rods and metallic rods. A single cell 3D structure has been theoretically designed and the cold test result will be presented.

ANISOTROPIC BAND GAP MAP

Sapphire is an optically anisotropic material with permittivity changing with the electromagnetic (EM) wave frequency [8]. At 17 GHz, with the orientation of the C-axis of the sapphire rods parallel to the particle beam axis in our design, the permittivity of the sapphire rod is $\epsilon_r = [9.398, 9.398, 11.587]$ by interpolation from [8].

Figure 1 shows the band gap map of a periodic sapphire lattice with the above anisotropic permittivity calculated in HFSS, as well as the comparison with an isotropic lattice of $\epsilon_r = 9.398$. The eigenmode frequency is normalized to $\omega b/2\pi c$ and the lattice is characterized by ratio $\frac{a}{b}$ with the rod radius a and the lattice spacing b. The lowest band gap can confine the TM_{02} mode while the TM_{01} mode is radiated out through the dielectric lattice.

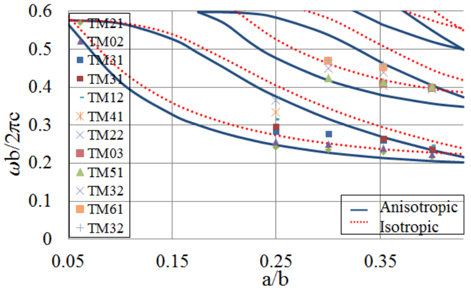


Figure 1: Band gap map of sapphire with isotropic and anisotropic permittivity.

In HFSS, to model a ”2D structure”, a very thin PBG layer is made with perfect E boundaries on top and bottom to limit the eigenmode solutions to TM modes. The calculated normalized frequencies of different modes in the 2D PBG structure are shown in Fig. 1; this helps to determine the design point $\frac{a}{b} \sim 0.35$, where the TM_{02} mode sits in the center of the band gap and few other modes are present in the same gap. The only HOM that is of concern is the TM_{31} mode. The final parameters of $a = 1.58$ mm and $b = 4.47$ mm have been chosen based on the 3D design shown later. Varying the arrangement of rods to achieve an improved Q of the TM_{02} mode and a reduced Q of the TM_{31} mode will be described in the following section.

CAVITY MODE IN 2D DESIGN

The birefringence of sapphire results in a discrepancy between the 2D and 3D simulations, but the study of the

---

* This work supported by Department of Energy High Energy Physics, Grant No. DE-SC0010075.

† zhangjx@mit.edu

2D cross section of each mode with distinct rod patterns provides a basic idea of how to improve the Q of the TM_{02} mode and damp the HOMs. Figure 2 shows how the diffractive Q of the TM_{02} mode increases as we include additional rows of concentric sapphire rods. This shows that a large number of rods are needed in a pure dielectric cavity to get a Q of the TM_{02} mode that is comparable to the Q of the TM_{01} mode in a DLW ($Q > 1000$), leading to a large cavity geometry. To increase the diffractive Q of the TM_{02} mode, metallic rods are added to the outermost row.

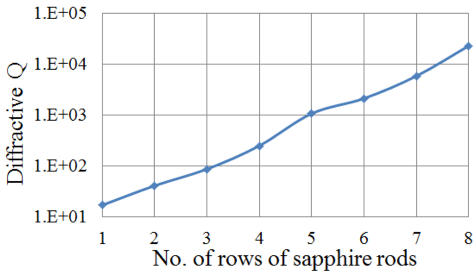
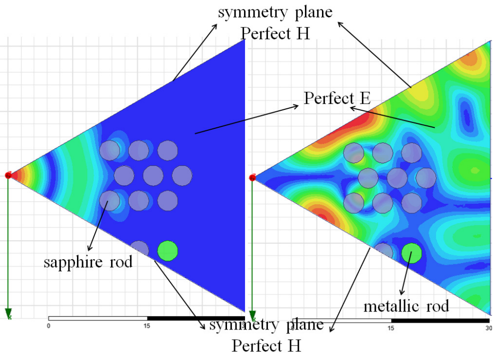


Figure 2: The diffractive Q vs. the number of concentric rows of sapphire rods.

Removing some rods makes the structure more azimuthally uniform and creates damping channels for the HOMs, which improves the Q of the TM_{02} mode and degrades the Q of the TM_{31} mode significantly. A 60° symmetric wedge of the optimal 2D structure is shown in Fig. 3, showing the E fields of the TM_{02} and TM_{31} modes. The calculated Q of the TM_{02} mode is $\sim$ 6500 and the Q of the TM_{31} mode is $\sim$ 30.



(a) TM02 (b) TM31

Figure 3: The 60° wedge cross section of E field of (a), the TM_{02} mode, and (b), the TM_{31} mode in the 2D model of the hybrid PBG structure.

SINGLE CELL 3D DESIGN

Based on the 2D design, a 3D HFSS model of a periodic single cell with three rows of sapphire rods and one row of metallic rods is shown in Fig. 4. Rods are inserted into two copper plates to form a cavity and irises are shaped to couple 17 GHz RF power. Design parameters are listed in Table 1.

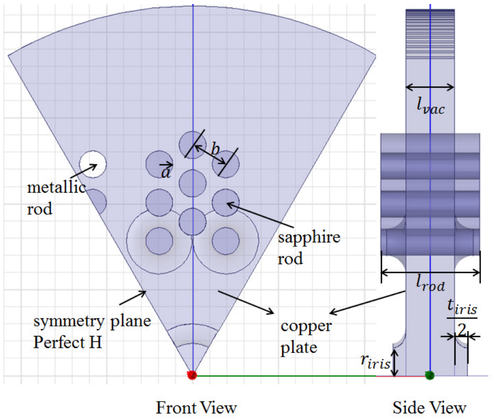


Figure 4: The 3D HFSS model of the periodic single cell hybrid PBG structure.

Table 1: Design Parameters of the Periodic Single Cell Structure

a **(mm)**	b **(mm)**	l_{rod} **(mm)**
1.58	4.47	11.68
r_{iris} **(mm)**	t_{iris} **(mm)**	l_{vac} **(mm)**
3.765	3.07	5.68

By using ”Master” and ”Slave” boundaries in HFSS, a phase shift of 180° is forced on the ends of irises to form a periodic boundary condition. The comparison of the EM field profile between the hybrid PBG cell (TM_{02} mode) and DLW cavity (TM_{01} mode) with the same irises is shown in Fig. 5, for an accelerating gradient [9] of 100 MV/m in each case.

The comparable field profile indicates a possibility to apply the hybrid PBG structure in high-gradient accelerators. The simulated result is listed in Table 2 as well as the experimental cold test measurement discussed next.

Table 2: Results of the Single Cell Structure

	f **(GHz)**	Q
Sim.	17.19	5800
Exp.	17.12	2700

SINGLE CELL COLD TEST

Cold test of a single cell of the hybrid PBG structure has been performed using a Vector Network Analyser (VNA) at MIT as shown in Fig. 6. Two antennas are held by three-axis translation stages to send and receive signals. Q is measured through the transmission parameter S_{21} [10].

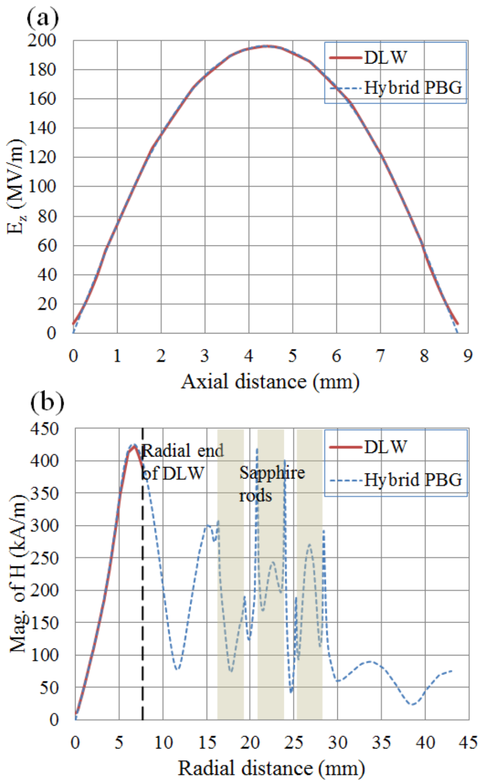


Figure 5: Comparison of the Hybrid PBG cell and the DLW cell of (a), E field axial profile and (b), H field radial profile.

The experimental result is shown in Fig. 7 with a single resonance at 17.12 GHz with $Q = 2700$, as listed in Table 2. No other modes are observed. The differences between theory and experiment in Table 2 may be due to approximations in the theory or fabrication errors. However, the presence of a single resonance close to the design frequency is very promising for future hot test experiments.

CONCLUSION

A hybrid PBG structure consisting of anisotropic dielectric rods and metallic rods has been optimized with 2D and 3D design in HFSS. With an accelerating gradient of 100 MV/m, the field profile of the single hybrid PBG cell is comparable to a DLW cell. A transmission measurement of a single cell of the hybrid PBG structure has been obtained in cold test, showing a single resonance at 17.12 GHz with a Q of 2700, providing a promising future for accelerator applications.

A SW 3-cell hybrid PBG structure is under design. By using the high power 17 GHz Haimson klystron at MIT, breakdown tests can be performed on the multi-cell structure.

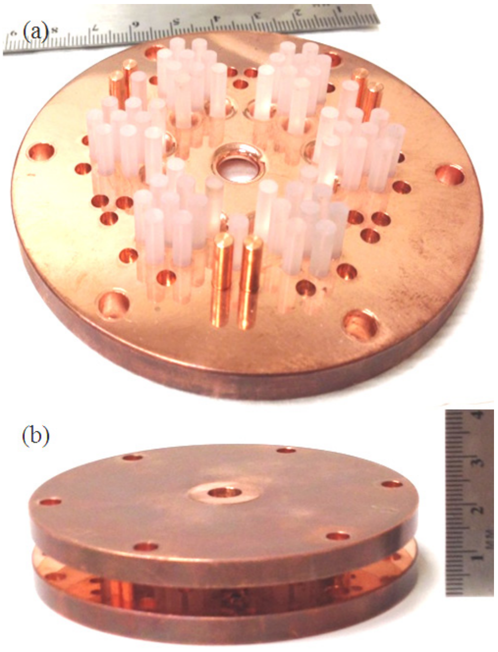


Figure 6: The cold test structure of the single hybrid PBG cell.

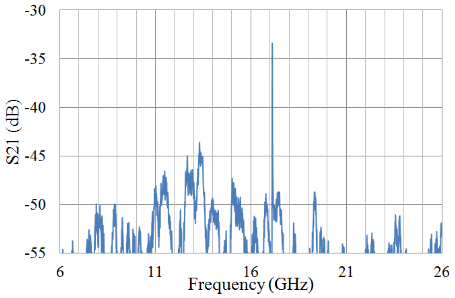


Figure 7: Transmission measurement of the single hybrid PBG cell.

REFERENCES

[1] S. Schultz, D.R. Smith and N. Kroll, ”Photonic Band Gap Resonators for High Energy Accelerators”, PAC’93 (1993).

[2] E.I. Smirnova et al., Phys. Rev. Lett. 95, 074812 (2005).

[3] R.A. Marsh, *Experimental Study of Photonic Band Gap Accelerator Structures*, MIT-Thesis (2009).

[4] B.J. Munroe et al., Phys. Rev. ST Accel. Beams 16, 012005 (2013).

[5] M.A. Shapiro et al., Proc. Par. Accel. Conf. (PAC’03), IEEE Conf. Prof., pp.1255-1257 (2003).

[6] A.M. Cook et al., PAC’11 Proc. MOP041, p.175 (2011).

[7] M.R. Masullo et al., Microwave Opt. Techn. Lett. 48, p.2486 (2006).

[8] J. Krupka et al., Meas. Sci. Tech. 10, pp. 387-392 (1999).

[9] T.P. Wangler, *RF Linear Accelerators*, (Wiley-VCH, 2008), p. 41.

[10] E.L. Ginzton, *Microwave Measurements*, (McGraw-Hill, 1957), p. 405.