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DESIGN AND HIGH-POWER TESTING OF A HYBRID PHOTONIC BAND-GAP (PBG) ACCELERATOR STRUCTURE AT 17 GHz*

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Abstract

An overmoded hybrid Photonic Band Gap (HPBG) structure used as an accelerator cavity has been theoretically designed and high power tested at 17.1 GHz. The HPBG structure consists of a triangular lattice of dielectric (sapphire) and metallic (copper) rods. Due to the frequency selectivity, the hybrid PBG cavity can be operated in a TM_{02} mode. The maximum surface fields are on the triple point of the innermost row of the sapphire rods. The relatively high value of the surface fields resulted in a high breakdown rate (BDR) at a low gradient in the HPBG structure. Breakdown damage on the triple point edge and the metallization of copper onto the sapphire surface have been observed in the post-testing images. An improved HPBG design, that reduces the peak fields, has been developed. It will be built and tested in an effort to improve the HPBG performance.

INTRODUCTION

A periodic photonic structure, whose dispersion relation has photonic band gaps (PBG), can be applied to accelerators due to its frequency selectivity [1]. A traveling-wave (TW) multi-cell metallic PBG structure has demonstrated successful acceleration of electrons with a gradient of 35 MV/m [2]. Standing-wave (SW) metallic PBG (MPBG) structures have been studied with high power to investigate the breakdown rate at both SLAC and MIT [3–6].

A dielectric PBG structure has been theoretically studied [7]. A sapphire rod structure was previously built and cold tested but not tested at high power [8]. A hybrid PBG structure using both dielectric (sapphire) and metallic (copper) rods to form the triangular lattice array for an accelerator cavity was presented by this author [9]. The dielectric band gap map was calculated using HFSS. Since the dielectric band gap map has no cut off frequency, an overmoded operation with the TM_{02} mode confined in a defect cavity can be chosen by adjusting the lattice ratio a/b, where a is the radius of the dielectric rod and b is the lattice constant. This helps in the design of the geometry for a high frequency of 17 GHz. The defect is formed by removing the first four rows of sapphire rods. Metallic rods are added on the outermost row to increase the reflection, thus increasing the quality factor Q of the accelerating mode. Different rod patterns can be arranged by removing rods to increase the azimuthal uniformity of the TM_{02} mode and damp the higher-order-modes (HOMs). Cold test showing a single resonance at the right frequency has demonstrated the overmoded excitation.

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In this paper, the design and the results of the high power testing of our first HPBG structure will be described. Post-test images will show some damage on both the dielectric and the metallic materials. An improved HPBG design to reduce the peak surface fields will be discussed.

EXPERIMENTAL DESIGN

To conveniently and comparably test the high power properties of a specific cavity, SLAC has developed a procedure of testing a single-cell, Standing-Wave cavity with two side cavities to concentrate the high field in the central test cavity [10]. The PBG structures tested at MIT follow the same design concept with a clamped assembly and scaled dimensions to match the resonant frequency of 17.14 GHz of the Haimson Research Corporation (HRC) klystron. Figure 1 shows the 3D model of the HPBG structure used in the SW test stand. A mode launcher is used to convert the rectangular waveguide mode to the input fundamental TM_{01} mode.

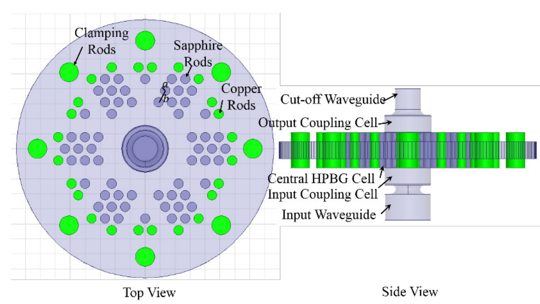

Figure 1: The SW model of the HPBG structure in the 3D simulation. Sapphire rods are shown in dark purple and metal rods in green.

The c-axis of each sapphire rod is aligned parallel to the longitudinal axis of the accelerator cavity. The birefringence of the sapphire gives a permittivity $\varepsilon_r = [9.398, 9.398, 11.587]$. The lattice parameters are a rod radius $a = 1.58$ mm and a rod spacing $b = 4.48$ mm. The length of the sapphire rods is 11.68 mm. Rods are inserted into copper plates with an insertion depth $d = 3$ mm. Fillets with a radius of $R_{fil} = 2.25$ mm are added on the triple point (the point where sapphire, copper and vacuum meet) of the six innermost rods to reduce the strong surface fields. The radius of the coupling iris is adjusted to obtain a critical coupling. The symmetry of the structure and the TM_{02} mode allows the simulation of the entire 360-degree structure with a 30-degree wedge. The final simulation result of S_{11} is shown in Figure 2. The resonant frequency f_0 and the quality factor Q_L are listed in Table 1. To compare, Figure 2 and Table 1 show results

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of the cold test before and after the high power testing, too, with details to be described in the next two sections.

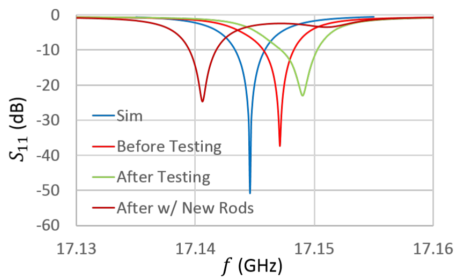

Figure 2: Comparison of S_{11} among the simulation and the cold test results before and after the high power testing.

Table 1: Comparison of f_0 and Q_L

	f_0 **(GHz)**	S_{11} **(dB)**	Q_L
Simulation	17.145	-51	2230
Before Testing	17.147	-37	2150
After Testing	17.149	-23	2010
After w/ New Rods	17.141	-24	2170

Comparison of the field profile of the accelerating field E_z is shown in Figure 3, with the high gradient occurring only in the central HPBG cell of the structure.

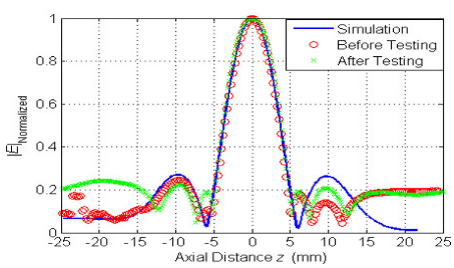

Figure 3: Comparison of the axial accelerating field profile.

The current design generates high surface electric (E) and magnetic (H) fields on the triple edge of the rods on the innermost row. Table 2 lists the maximum surface fields normalized to E_G = 100 MV/m.

EXPERIMENTAL RESULTS

The high power experiment for the HPBG structure is to test the breakdown properties of the PBG structure with the dielectric material. The metallic parts were machined by the MIT Central Machine Shop. The sapphire rods were produced by Insaco Inc. Figure 4 shows all the components of the HPBG structure.

By employing an Agilent E8363B Vector Network Analyzer (VNA), the cold test result gave a good resonance at 17.147 GHz, as shown in Figure 2 and Table 1. A non-resonant bead pull measurement was performed to measure the axial field profile, with the result shown in Figure 3.

Table 2: The Maximum Surface Fields of the HPBG Structure

E_G **(MV/m)**	E_{surf} **(MV/m)**	$H_{surf}(kA/m)$
100	628	2295

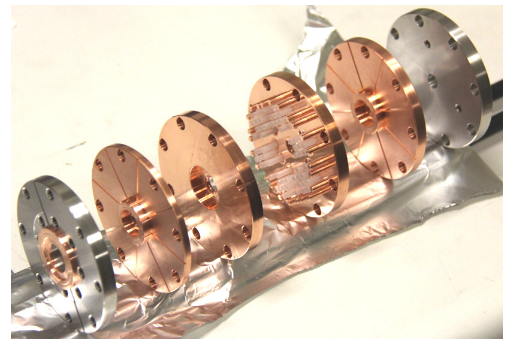

Figure 4: Components of the HPBG structure, including (left to right) the input flange with a copper gasket; the input coupling cell; a rod plate with holes for insertion of rods forming the upstream side of the HPBG cell; the downstream HPBG cell plate with 60 sapphire and 24 OFHC copper rods inserted; the output coupling cell; the output flange.

The high power testing was conducted using the HRC klystron at the MIT Accelerator Laboratory. Two diodes were used to measure the forward power and the reverse power, respectively. The structure power and the gradient were calculated using the forward power. Each breakdown event was determined by the reflected power and the dark currents measured by two current monitors. A Thorlabs 8050M-GE 8 Megapixel Monochrome CCD Camera was employed to capture the light in the HPBG cell during breakdown events.

The high power testing lasted for one month, including two phases, 458,000 shots in total. Phase 1 started at $E_G \sim 1$ MV/m with breakdown observed on every shot at $E_G \sim 3$ MV/m. The dark current of the HPBG structure was relatively high ($\sim$ 10 mA at $E_G \sim 5$ MV/m, for example). To facilitate the processing, we gradually increased the input power neglecting the large dark current and the high breakdown rate, until the gradient reached $\sim$ 14 MV/m. The pulse length of the input power was kept at 100 ns.

After 222,000 shots of processing in Phase 1, the structure gave lower dark currents and breakdown rates in Phase 2. Phase 2 includes 236,000 shots and three input pulse lengths: 100 ns, 160 ns and 210 ns, corresponding to a 40-ns, a 80-ns and a 130-ns flat top of the structure power, respectively. For each new gradient level, a few shots were needed to re-condition the structure. During re-conditioning, the peak of the dark current decreased gradually until reaching a constant level. This level of dark current in Phase 2 was much lower than in Phase 1 ($\sim$ 1 mA at $E_G \sim 5$ MV/m, for example). The structure came to a quasi-steady state with a constant BDR, with the result shown in Figure 5. The highest gradient achieved with a 80-ns flat-topped structure power is 8.8 MV/m, with a BDR of 1.28×10^{-1} /pulse/m.

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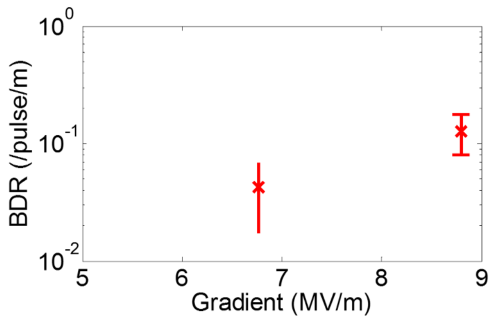

Figure 5: Breakdown probability as a function of gradient for the HPBG structure, with a 80-ns flat top of the structure power.

Increasing the gradient to 9.6 MV/m resulted in a runaway condition with chains of breakdowns.

Light on the sapphire rods was observed for all of the shots with $E_G > 5.7$ MV/m, even without breakdown, indicating the occurrence of multipactor and plasma formation.

DAMAGE INVESTIGATION

The cold test after high power testing, as shown in Figure 2 and Table 1, resulted in a small reduction of Q_L. Changing to a new set of sapphire rods led to a higher Q_L, indicating that the measured change in Q_L was within our experimental measurement accuracy and was therefore the result of damage to the sapphire rods. Post-testing images of the structure showed that at the location of the triple point with the highest calculated E-field, significant damage was observed.

IMPROVED HPBG DESIGN

The first design of the HPBG structure had a very high ratio of surface field to gradient, $E_{surf}/E_G \sim 6$. Further research has been conducted leading to new HPBG designs that greatly reduce this ratio, hopefully allowing us to reach higher gradient in future testing. Figure 6 shows the HFSS model of one example of an improved HPBG cell, along with the simulated E and H field normalized to $E_G = 100$ MV/m. The new design results in greatly reduced surface fields, $E_{surf,\max} = 216$ MV/m and $H_{surf,\max} = 1.2 \times 10^3$ kA/m, thus $E_{surf}/E_G \sim 2.2$, comparable to the metallic PBG structure tested at MIT. This new design is to be machined and high power tested soon.

CONCLUSION

The first high power testing of the hybrid PBG structure has been conducted at MIT at 17 GHz, resulting in a breakdown rate of $1.29{\times}10^{-1}$ /pulse/m at a gradient of 8.8 MV/m for a 80-ns flat top pulse of the structure power. A reduction of the quality factor was measured after high power testing and breakdown damage was observed on both the copper plate and the sapphire rods. The metallization from copper onto the surface of the sapphire rods can change the quality factor of the cavity, which is a potential disadvantage of the hybrid design. The relatively high dark current and the high breakdown probability was caused by the strong surface fields and the field enhancement on the triple point of the first row of the sapphire rods. An improved design has been developed that should hopefully lead to much higher gradient operation.

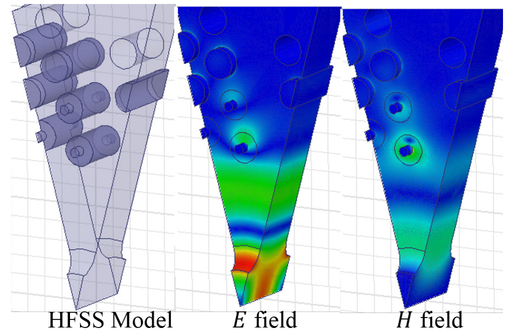

Figure 6: The HFSS model and the E and H field plots of the HPBG cell with the new "rolling pin" sapphire rods mixed with regular rods of insertion length $d = 1$ mm.

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