PHOTONIC BAND GAP ACCELERATOR DEMONSTRATION AT KU-BAND

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Abstract

We report the successful cold test and hot test demonstrations of a metal Ku-band PBG accelerator structure. The 17.140 GHz 6-cell PBG accelerator structure with reduced long-range wakefields was designed for the experiment. The copper structure was electroformed and cold-tested. Tuning was performed through chemical etching of the rods. Final cold test measurements were found to be in very good agreement with the design. The structure was installed on the beam line at the accelerator laboratory at Massachusetts Institute of Technology and powered with 2 MW of peak power from the 17.14 GHz klystron. The electron beam was accelerated by 1.4 MeV inside the PBG accelerator, which is in excellent agreement with the predicted accelerating gradient of 35 MV/m.

INTRODUCTION

Metallic photonic band gap (PBG) structures have received considerable attention recently, because of their remarkable abilities to selectively confine modes [1,2]. PBG structures reflect waves in certain ranges of frequencies (called global band gaps) while allowing other frequencies to propagate. A defect in periodic structure forms “PBG cavity” in which a mode with the frequency inside the global band gap can be confined, but modes with the frequencies outside the global band gap cannot. Thus, it is possible to design a PBG cavity, which would selectively confine the accelerating TM01-like mode and will not support the higher order modes, such as the next higher order the TM11-like mode, which is a dangerous wakefield mode, primarily responsible for degrading the electron beam quality in accelerators.

At MIT, we made significant efforts on investigating the PBG structures based on triangular lattice of metal rods. We designed a PBG cavity formed by a missing rod in the triangular lattice. We derived the conditions, for which this resonator would selectively confine the TM01-like mode [3,4]. We have constructed multiple PBG resonators and proved the selective confinement of the TM01-like mode in cold tests. In addition, we demonstrated the construction of high-Q PBG resonators [5].

Next, we have proposed to use the PBG cavity supporting a single TM01-like mode as an accelerator cell and construct a disk-loaded 2π/3 accelerator structure with a stack of six PBG cavities set between the disks with the beam holes (Fig. 1). A complete design of a 6-cell PBG accelerator structure was performed [5]. This paper reports the results of the construction, cold testing and hot testing of a 6-cell PBG accelerator structure. The PBG accelerator was successfully demonstrated and the electron beam was accelerated by 1.4 MeV inside the PBG structure.

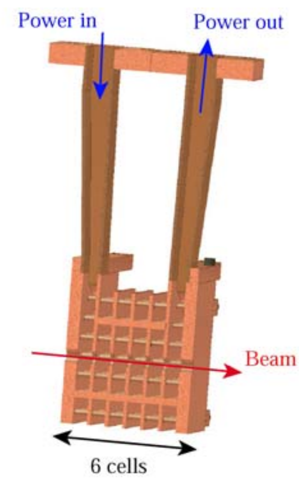

Figure 1: Cut away drawing of a six-cell PBG accelerator.

Table 1. The dimensions and accelerator characteristics of the 2π/3 PBG accelerator structure.

Rod radius (structure/coupler cell)	1.04/1.05 mm
Rod spacing	6.97 mm
Cavity length	5.83 mm
Iris radius	2.16 mm
Iris thickness	1.14 mm
Freq. (TM_{01})	17.140 GHz
Shunt impedance, r_s	98 MΩ/m
$[r_s/Q_w]$	23.4 kΩ/m
Group velocity	0.013 c
Gradient	$25.2\sqrt{P[MW]}$ MV/m

THE PBG ACCELERATOR CONSTRUCTION AND COLD TEST

The dimensions and the accelerator characteristics of the PBG structure are summarized in Table 1. The structure was fabricated via electroforming, which was performed by the Custom Microwave, Inc [6]. The

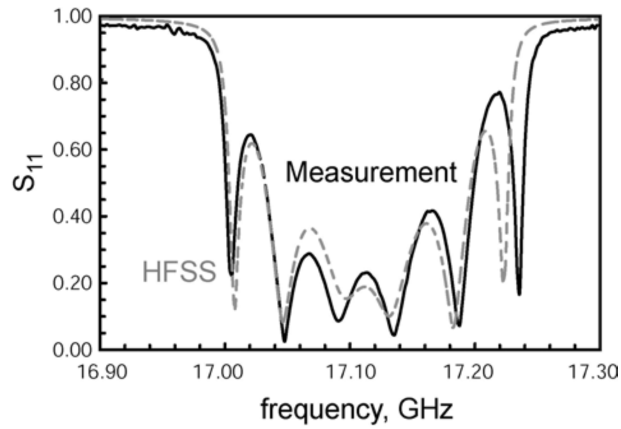

Figure 2: Comparison between the computed and measured S_{11} coupling curves for the 6-cell PBG accelerator structure.

aluminum mandrels with holes in place of the rods were fabricated first. Then the mandrels were placed into a copper solution. Copper ions were deposited on the mandrels, and PBG cells consisting of the rods and two half-plates were formed. Then the aluminum was etched. Cells were put together and soldered. Copper was flashed over the whole structure to cover the solder in the joints.

The initial comparison of the measured and computed reflection curves indicated that the fabricated structure was 40 MHz higher in frequency than the design. Tuning was required. In addition, the resonance frequencies of each traveling wave cell were measured. It was found that two cells were 10 MHz lower in frequency than the other four cells. Thus, two cells had to be tuned differently.

Tuning was performed by chemical etching of copper rods. The structure was mounted on a stainless steel rod, about 12 inches in length. The rod was wrapped with heat shrink tubing and tape to a diameter that provided a press fit into the beam hole of the structure and then was inserted into the beam hole. This served both to mask the beam hole and as a handle for the dipping operation. Jack-o-lantern candles were melted on a hot plate and served as a masking material for two cells which were low in frequency. Acid solution was mixed as follows: 100 ml nitric acid, 275 ml phosphoric acid, and 125 ml acetic acid. This solution was used at 45 ^{0}C and removed 0.0001” per minute from each side of copper rods. The whole structure was etched for 3 minutes. Next, two cells with low frequencies were masked and the rest of the structure was etched for one more minute. Finally, the wax was removed with a detergent cleaner in an ultrasonic tank at 70 ^{0}C.

The tuned structure was cold-tested again. The measured reflection (S_{11}) curve is shown in Fig. 2. For comparison, the computed S_{11} curve is shown. There is an excellent agreement between the measured and the computed curves. The reason for the slightly increased dispersion of the measured curve is the etching process. While the etching decreased the rods diameter it also decreased the plate thickness and thus increased the dispersion.

THE PBG ACCELERATOR DEMONSTRATION IN A HOT TEST

The PBG structure was installed inside a vacuum chamber at the end of the MIT linac beamline. A diagram of the MIT accelerator experimental laboratory is shown in Fig. 3. The Haimson Research Corporation (HRC) relativistic klystron amplifier [7] was employed to supply the power for the linac and the PBG structure. The klystron was operated at 10 to 15 MW for 100 ns. The klystron output is connected to a power splitter which directs the power into two WR-62 output waveguide arms. The power level ratio between the arms can be varied. One arm is directed towards the linac and the second arm goes to the PBG structure. A phase shifter was installed on the PBG experiment arm to allow for different phase shifts between the field in the linac and in the PBG accelerator.

The linac beam represented a train of 0.01 nC, 1 ps bunches at 17.140 GHz with an energy of 10-25 MeV [8]. At 0.5 m beyond the linac on the beamline, a focusing solenoid produces magnetic fields up to 0.6 T, which provide a minimum beam spot size at the PBG structure of about 1 mm. A set of steering coils provided a means to center the beam on the PBG accelerator structure axis. A magnetic spectrometer was installed at the end of the beamline and employed for measurements of the beam energy.

The PBG accelerator structure was conditioned over a period of 1 week (approximately 100,000 pulses). Up to 2 MW of microwave power at 17.140 GHz in a 100 ns long pulse could be coupled into the PBG structure without breakdown. The filling time of the PBG structure is less than 10 ns. With 2 MW of input power, the calculated accelerating gradient in the PBG structure is 35 MV/m.

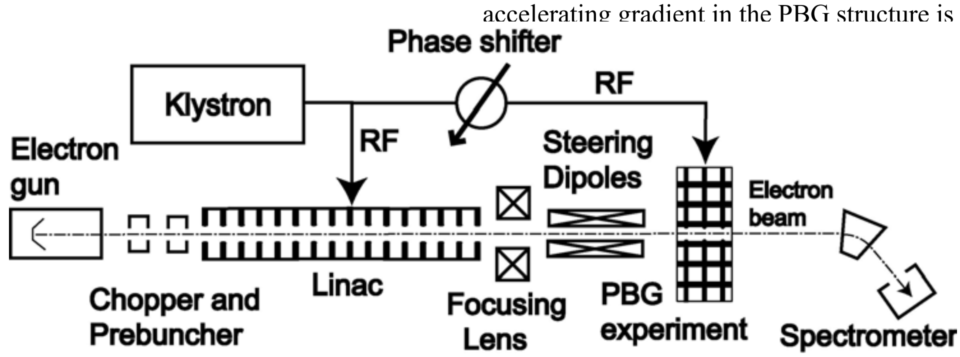

Figure 3: The hot test experimental setup schematics.

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The energy spectrum of the linac electron beam was determined first. For 10.5 MW of 17.140 GHz input power to the linac, the linac electron beam had energy of 16.5 MeV with an energy spread of +/-0.25 MeV (Fig. 4). Next, the phase shift between the linac and the PBG accelerator was scanned until the two were found to be in phase, thus allowing for the maximum energy gain. The electron beam energy gain was measured for different input powers into the PBG accelerator. The results are shown in Fig. 5. The beam energy increases as the square root of the input power as expected from theory. Maximum energy gain for 2 MW of input power was found to be 1.4 MeV which is consistent with the estimated 35 MV/m accelerating gradient.

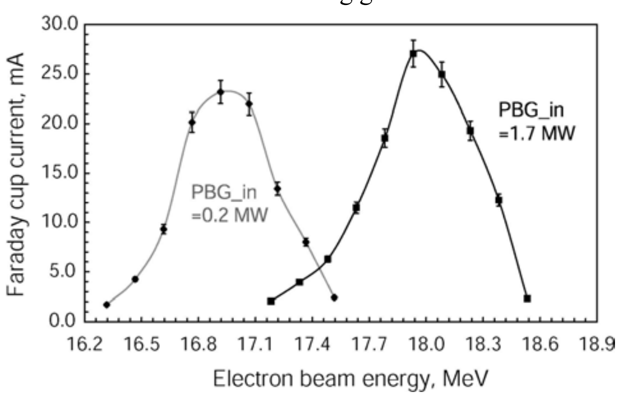

Figure 4: The Faraday cup signal at the 30-degree-bend spectrometer arm versus the electron beam energy for different input powers into the PBG accelerator.

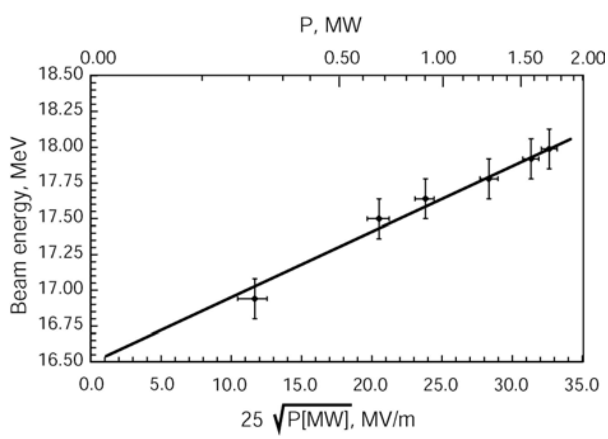

Figure 5: Measured energy of the electron beam versus square root of the PBG accelerator input power, P.

CONCLUSION

This work was performed to construct the first travelling wave linear photonic band gap accelerator structure. The advantage of the PBG accelerator over the conventional disk-loaded accelerator is the efficient long-range wakefields suppression. Suppression of wakefields would allow scientists to extend the operating frequencies of future linear colliders to higher frequencies without sacrificing the beam quality.

First, PBG resonators were studied and the design of a resonator which would completely suppress the wakefields was presented [4]. Numerous 2D PBG resonators were constructed and tested [4,5]. Two goals were achieved: the 2D metallic PBG structures theory and simulations were benchmarked, and single-mode confinement in a PBG resonator was proven. Engineering efforts were undertaken to successfully demonstrate a high Q PBG resonator. Brazing was used to provide electrical contact between metallic rods and plates [5].

Second, the first travelling-wave PBG accelerator structure was proposed [5]. The first PBG coupler with excellent mode symmetry was designed. Computational techniques for PBG couplers tuning were developed. The PBG traveling-wave structure was manufactured by electroforming. The electroforming proved to be a good technique for fabrication of multi-cell PBG structures. The tuning of the PBG accelerator structure was performed via etching. The cold tests of the tuned structure were in perfect agreement with computations.

Finally, high gradient electron beam acceleration in a Photonic Band Gap accelerator was demonstrated. The additional electron beam energy gain of 1.4 MeV was observed due to the acceleration inside of the PBG structure.

Future research on PBG accelerators should be directed towards improved fabrication techniques, studies of microwave breakdown and direct tests of wakefield suppression.

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