Demonstration of a 17-GHz, High-Gradient Accelerator with a Photonic-Band-Gap Structure

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We report the testing of a high gradient electron accelerator with a photonic-band-gap (PBG) structure. The photonic-band-gap structure confines a fundamental TM_{01}-like accelerating mode, but does not support higher-order modes (HOM). The absence of HOM is a major advantage of the PBG accelerator, since it suppresses dangerous beam instabilities caused by wakefields. The PBG structure was designed as a triangular lattice of metal rods with a missing central rod forming a defect confining the TM_{01}-like mode and allowing the electron beam to propagate along the axis. The design frequency of the six-cell structure was 17.14 GHz. The PBG structure was excited by 2 MW, 100 ns pulses. A 16.5 MeV electron beam was transmitted through the PBG accelerator. The observed electron beam energy gain of 1.4 MeV corresponds to an accelerating gradient of 35 MV/m, in excellent agreement with theory.

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To probe beyond the established picture of particle physics, accelerators must reach ever-higher energies into the TeV range. Intensive research is being conducted on novel acceleration techniques, which would allow high particle beam energies to be achieved by means of high gradient acceleration, thus minimizing the accelerator cost and complexity. These advanced accelerators are also needed for free electron lasers at wavelengths up to the x-ray region, and compact industrial accelerators. Promising approaches include laser-beat-wave accelerators [1–3], laser-wakefield accelerators [4,5], plasma wakefield accelerators [6], and other novel ideas [7,8]. Another promising approach consists of using high frequency microwaves (10 to 100 GHz) to produce higher gradient accelerators than those obtained by operating at present day microwave frequencies (3 GHz or less). High frequency accelerators also operate at reduced stored energy and power consumption [9,10]. High power, high frequency microwave sources are expected to have major advantages in terms of high average power capability and high efficiency operation. However, wakefield radiation from bunched beams can excite high order modes (HOM) in an accelerator, leading to beam breakup instabilities and ultimately to beam loss from the accelerator [11]. Wakefield generation is known to scale as frequency to the third power, a very dangerous situation for high frequency microwave accelerators [12]. The research that is reported here demonstrates a novel, high gradient acceleration structure for high frequency microwaves which can mitigate and even eliminate the problem of dangerous wakefield radiation. Until now, photonic-band-gap (PBG) cavities have not been tested in an accelerator (hot tested) to demonstrate that they can be built and operated at high gradient. We report the successful fabrication, tuning, and operation up to an accelerating gradient of 35 MeV/m of a six-cell PBG structure.

The accelerator structure based on a disk-loaded PBG waveguide is shown schematically in Fig. 1. A PBG structure (or simply, photonic crystal) represents a periodic lattice of macroscopic pieces of dielectric or metal [13]. Scattering of the electromagnetic waves on the periodic structure can produce many of the same phenomena for photons that the periodic atomic potential does for electrons [14]. In particular, one can design and construct photonic crystals, preventing light of certain frequencies from propagating in certain directions. The range of frequencies which do not propagate through the photonic crystal is called a “band gap.”

A periodic lattice of metal rods, which is a particular case of a two-dimensional (2D) photonic crystal, is attractive for microwave applications [15–17]. The presence of a photonic band gap in a 2D photonic crystal allows construction of a PBG waveguide, which can be formed by removing a rod from the center of the lattice as shown in Fig. 1. The mode, which has a frequency in the band gap, will not be able to propagate out transversely through the bulk of the PBG structure and will thus be localized around the defect. However, generally, PBG waveguides only support modes with frequencies within the global band gaps and therefore provide a means for selective suppression of unwanted (high order/wakefield) modes.

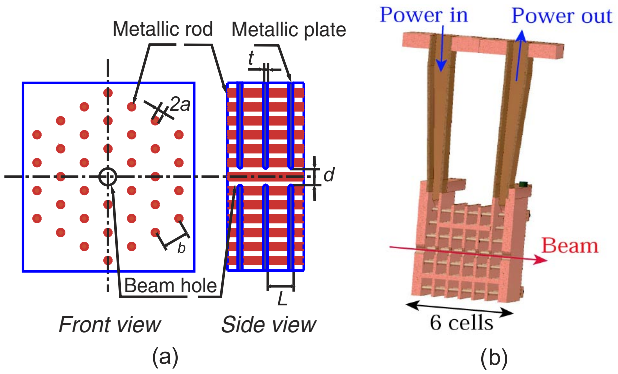

FIG. 1 (color online). (a) Schematics of the disk-loaded PBG waveguide. (b) Cut away drawing of a six-cell PBG accelerator.

Numerous advances have been made in the theory of 2D PBG structures and 2D metallic PBG resonators and waveguides. The complete diagrams of global band gaps in square and triangular 2D metallic lattices of rods have been published in [18]. A 2D metallic PBG resonator for accelerator applications, based on a square lattice was first investigated computationally by Smith *et al.* [15,16]. This first investigation was very promising but it also had certain drawbacks. First, it did not completely demonstrate the selective single-mode confinement in a PBG resonator. Second, it was later shown that the use of a square lattice provides poor azimuthal symmetry [17]. We have developed the triangular lattice resonator, which provides much better azimuthal symmetry. Using the band gap diagrams computed in [18], we have designed a PBG resonator, which supports a single transverse-magnetic (TM) mode and no HOM [19]. The field profile of the confined mode in a PBG resonator closely resembles the field profile of the TM_{01} mode of a pillbox cavity (Fig. 2), which is conventionally employed as the accelerating mode in disk-loaded cylindrical waveguides. It was shown in [19] that a PBG resonator with a triangular lattice selectively supports the TM_{01} mode only if the radius of the rods in the PBG resonator, a, divided by the spacing between the rods, b, is less than 0.2. When $a/b < 0.2$, the next higher-order TM_{11}-like mode cannot be supported by the PBG structure [Fig. 2(a)]. For $a/b \geq 0.2$ the TM_{11}-like mode is confined by the PBG structure [Fig. 2(b)] and the PBG resonator is not mode selective and is not attractive as an accelerator cell, since the TM_{11} dipole mode may induce the transverse beam displacement. In Fig. 2(a), the mode observable in the simulation, labeled "dipole mode," is not confined within the central region, but instead extends throughout the volume of the resonator. The mode is only confined by the outer wall of the resonator. In our resonator, the outer wall is removed and this dipole mode is absent.

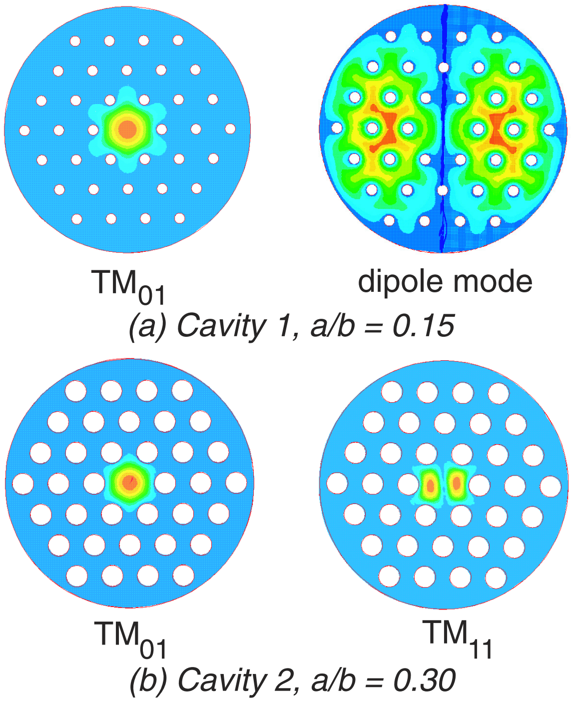

FIG. 2 (color online). Electric field patterns in the TM_{01}-like mode and the TM_{11}-like mode in a PBG waveguide: (a) the TM_{11}-like mode is not supported by the PBG structure when $a/b < 0.2$; (b) the TM_{11}-like mode is confined by the PBG structure when $a/b > 0.2$ (see [19]). The calculations have been made using the HFSS code [20].

The PBG accelerator was designed to operate at the MIT accelerator laboratory frequency of 17.140 GHz. As shown in Fig. 1, a PBG waveguide is formed by removing the central rod from a triangular lattice. The waveguide is loaded with iris plates to achieve resonance of the electromagnetic wave with the speed-of-light ($\gamma \sim 30$) electron beam. The iris plates spacing, L, is determined by the resonance condition

$$\frac{\omega L}{c} = \frac{2\pi}{3}, \tag{1}$$

where $\omega = 2\pi f$, $f = 17.140$ GHz is the accelerator frequency, and c is the speed of light. The iris plates have round openings at the center for transmitting the electron beam [Fig. 1(b)]. The diameter of the openings, $d = 4.32$ mm, is compatible with the waist size of the electron beam at the MIT accelerator laboratory. The traveling wave PBG structure was designed to consist of six cells: two coupler cells and four traveling wave (TW) cells.

The complete design of the structure was performed using the High Frequency Structure Simulator (HFSS) code [20]. The radii of the rods, a, and the spacing between the rods, b, were adjusted to bring the operating mode's frequency to 17.140 GHz. Both a and b could be varied to change the frequency. However, it was desirable to keep the ratio $a/b \approx 0.15$ for good HOM damping and high Ohmic Q [19]. An iris thickness $t = 1.14$ mm was chosen. The value selected for the iris thickness resulted in a low value of the group velocity, $0.013c$, but a high value of the shunt impedance. The high value of shunt impedance was necessary to produce a high accelerating gradient, so that, for the 2 MW of input power available from the klystron, the 6-cell structure could accelerate the electron beam by more than 1 MeV. This energy increase could then be easily detected, even in the presence of an energy spread that could be as large as ± 0.25 MeV. Finally, the HFSS code was applied for the coupler cell design. We employed the coupler tuning algorithm described originally in [21]. Final PBG accelerator structure dimensions and accelerator characteristics are summarized in Table I.

The PBG accelerator structure was manufactured via electroforming and was first found to be about 40 MHz too high in frequency. The structure was then fine-tuned to the correct frequency by chemical etching of the copper rods. Final manufacturing tolerance after tuning was

TABLE I. The dimensions and accelerator characteristics of the PBG accelerator structure.

Rod radius (TW cell/coupler cell), a	1.04 mm/1.05 mm
Spacing between the rods, b	6.97 mm
Plates spacing, L	5.83 mm
Iris radius, $d/2$	2.16 mm
Iris thickness, t	1.14 mm
Frequency (TM_{01} mode)	17.140 GHz
Ohmic Q factor, Q_w	4188
Shunt impedance, r_s	98 MΩ/m
$[r_s/Q_w]$	23.4 kΩ/m
Group velocity	0.013c
Gradient	$25.2\sqrt{P[\mathrm{MW}]}$ MV/m

2.5 microns (0.0001 inch). The comparison of the S_{11} (reflection) and the S_{21} (transmission) coupling curves measured after the fine-tuning in cold test to the coupling curves computed with HFSS is shown in Fig. 3. Agreement is excellent. The PBG structure was installed inside a vacuum chamber at the end of the MIT linear accelerator (linac) beam line. A diagram of the MIT accelerator experimental laboratory is shown in Fig. 4. The Haimson Research Corporation (HRC) relativistic klystron amplifier [22] was employed to supply the power for the linac and the PBG structure. The klystron is designed to produce up to 25 MW of rf power at 17.132–17.142 GHz for pulse lengths up to 1 μs and is typically operated at 10 to 15 MW for 100 to 150 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 was generated by a dc (Pierce) electron gun at the energy of 0.51 MeV with a normalized rms emittance of 1.8π mm-mrad and transported to the chopper-prebuncher section and the main linac. The resulting beam represents a train of 0.01 nC, 1 ps bunches at 17.140 GHz with an energy of 10–25 MeV [23,24]. At 0.5 m beyond the linac on the beam line, a focusing solenoid produces magnetic fields up to 0.6 T, which provide a minimum beam spot size of about 1 mm. The focusing solenoid and 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 beam line and employed for measurements of changes in beam energy (acceleration/deceleration). 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.

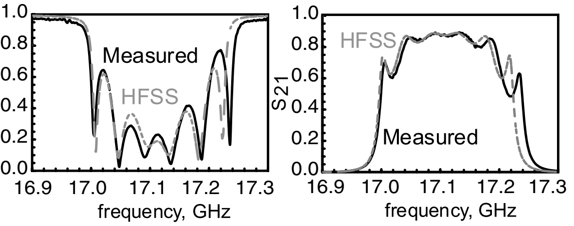

FIG. 3. Comparison between the computed and the final measured S_{11} (reflection) and S_{21} (transmission) coupling curves for the PBG accelerator structure.

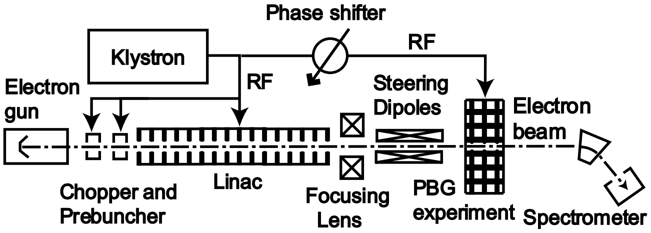

FIG. 4. Schematics (not to scale) showing the experimental linac, klystron, PBG structure, and spectrometer.

The energy spectrum of the linac electron beam was first determined with no power injected into the PBG structure. For 10.5 MW of 17.140 GHz input power to the linac, the linac electron beam had an energy of 16.5 MeV with an energy spread of ±0.25 MeV. Next, 17.140 GHz microwave power was supplied to the PBG accelerator. 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 was measured for different input powers into the PBG accelerator. The results are shown in Fig. 5. It was found that 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

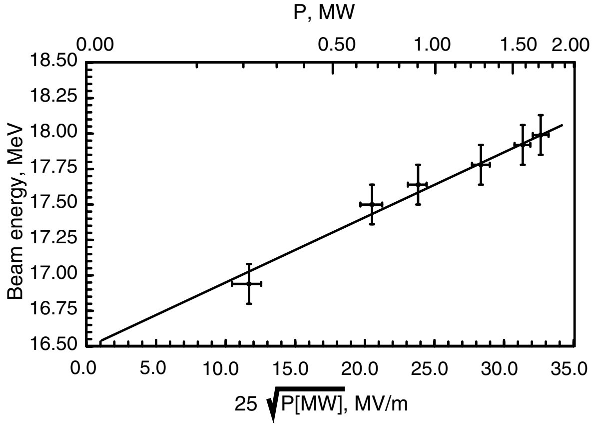

FIG. 5. Measured energy of the electron beam vs square root of the PBG accelerator input power, P.

which is consistent with the estimated 35 MV/m accelerating gradient.

We have demonstrated high gradient electron beam acceleration in a photonic-band-gap accelerator. The PBG disk-loaded waveguide may be a promising candidate for future accelerator applications because of its ability to effectively damp higher-order modes and thus suppress wakefields. The present research has demonstrated the ability to design, fabricate, and tune a PBG accelerator structure, and has shown that the structure does in fact accelerate electrons at high gradient. 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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[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[2] S. Y. Tochitsky, R. Narang, C. V. Filip, P. Musumeci, C. E. Clayton, R. B. Yoder, K. A. Marsh, J. B. Rosenzweig, C. Pellegrini, and C. Joshi, Phys. Rev. Lett. **92**, 095004 (2004).
[3] R. R. Lindberg, A. E. Charman, J. S. Wurtele, and L. Friedland, Phys. Rev. Lett. **93**, 055001 (2004).
[4] W. P. Leemans, P. Catravas, E. Esarey, C. G. R. Geddes, C. Toth, R. Trines, C. B. Schroeder, B. A. Shadwick, J. van Tilborg, and J. Faure, Phys. Rev. Lett. **89**, 174802 (2002).
[5] A. J. W. Reitsma, R. A. Cairns, R. Bingham, and D. A. Jaroszynski, Phys. Rev. Lett. **94**, 085004 (2005).
[6] P. Muggli, B. E. Blue, C. E. Clayton, S. Deng, F.-J. Decker, M. J. Hogan, C. Huang, R. Iverson, C. Joshi, T. C. Katsouleas, S. Lee, W. Lu, K. A. Marsh, W. B. Mori, C. L. O'Connell, P. Raimondi, R. Siemann, and D. Walz, Phys. Rev. Lett. **93**, 014802 (2004).
[7] *Advanced Accelerator Concepts, AIP Conference Proceedings*, edited by V. Yakimenko (AIP, New York, 2004), Vol. 737.
[8] C. Joshi and T. Katsouleas, Phys. Today **56**, No. 6, 47 (2003).
[9] H. H. Braun, S. Dobert, I. Wilson, and W. Wuensch, Phys. Rev. Lett. **90**, 224801 (2003).
[10] M. E. Hill, C. Adolphsen, W. Baumgartner, R. S. Callin, X. E. Lin, M. Seidel, T. Slaton, and D. H. Whittum, Phys. Rev. Lett. **87**, 094801 (2001).
[11] C. Adolphsen, K. Bane, T. Higo, K. Kubo, R. Miller, R. Ruth, K. Thompson, and J. Wang, Phys. Rev. Lett. **74**, 2475 (1995).
[12] K. Bane and M. Sands, Stanford Linear Accelerator Center Report No. SLAC-PUB-4441, 1987 (unpublished).
[13] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).
[14] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, Princeton, NJ, 1995).
[15] D. R. Smith, S. Schultz, N. Kroll, M. Sigalas, K. M. Ho, and C. M. Souloulis, Appl. Phys. Lett. **65**, 645 (1994).
[16] D. R. Smith, D. Li, D. C. Vier, N. Kroll, and S. Schultz, AIP Conf. Proc. **398**, 518 (1997).
[17] M. A. Shapiro, W. J. Brown, I. Mastovsky, J. R. Sirigiri, and R. J. Temkin, Phys. Rev. ST Accel. Beams **4**, 042001 (2001).
[18] E. I. Smirnova, C. Chen, M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin, J. Appl. Phys. **91**, 960 (2002).
[19] E. I. Smirnova, M. A. Shapiro, C. Chen, and R. J. Temkin, AIP Conf. Proc. **647**, 383 (2002).
[20] High Frequency Structure Simulator, www.hfss.com, Ansoft Corporation, Pittsburgh, PA 15219.
[21] N. M. Kroll, C. K. Ng, and D. C. Vier, Stanford Linear Accelerator Center Report No. SLAC-PUB-8614, 2000 (unpublished).
[22] J. Haimson, B. Mecklenburg, G. Stowell, K. E. Kreischer, and I. Mastovsky, AIP Conf. Proc. **474**, 137 (1999).
[23] J. Haimson and B. Mecklenburg, *Proceedings of the 1995 Particle Accelerator Conference* (IEEE, Piscataway, NJ, 1995), Vol. 2, p. 755.
[24] J. Haimson, B. Mecklenburg, and G. Stowell, *Proceedings of the 2001 Particle Accelerator Conference*, edited by P. Lucas and S. Webber (IEEE, Piscataway, NJ, 2001), Vol. 5, p. 3948.